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RESEARCH ARTICLE

Investigating Impacts of CVR and Demand Response Operations on a Bi-Level Market-Clearing With a Dynamic Nodal Pricing

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ABSTRACT This paper investigates the impacts of conservation voltage reduction (CVR) on electricity prices, the local market, and technical issues in distribution networks. An increase in electricity demand is one of the key challenges for developing sustainable societies. An increase in electric consumption puts immense pressure on electricity providers, which forces them to apply for load reduction programs during peak-demand time intervals. The CVR is one of the popular methods for load reduction, but how it would impact the pricing process and electricity market at the distribution level needs further investigation. The proposed methodology includes a power tracing and loss allocation-based pricing method. Since the distribution networks are going to be confronted by penetration of distributed energy resources (DER), prosumers, and microgrids, it is important to have a comprehensive methodology. This paper deploys a bi-level optimization algorithm to consider the financial benefits of all participating agents. In addition to CVR, the demand response (DR) programs are considered to shift and curtail flexible loads by the distribution system operator (DSO) and prosumers, respectively. The price sensitivity of prosumers toward change in the network's voltage for better planning is calculated. The operation costs/profits of DSO/prosumers decrease/increase during CVR and DR programs by 4.63% / 3%, respectively.

INDEX TERMS Conservation voltage reduction, demand response, power tracing, loss allocation, nodal pricing, bi-level optimization.

NOMENCLATURE

A. INDICES

m/n	Index of bus.
g	Index of distributed generator (DG).
t	Index of time interval.
k	Index of iteration.
c	Index of upstream-grid.
i	Index of prosumer.
j	Index of prosumer's DGs.

B. SETS

Γ_B	Set for bus.
Γ_{Bm}	Set for bus connectivity.
Γ_{DG}	Set for DG.
Γ_{DGm}	Set for DG's connectivity.
Γ_C	Set for upstream-grid.
Γ_T	Set for time interval.
Γ_P	Set for prosumer.
Γ_{Pm}	Set for prosumer's DGs.
Π_{DG}	Set for Prosumer's connectivity.
Π_{DGi}	Set for prosumer's DGs connectivity.

C. PARAMETERS

a^{DG}, b^{DG}, c^{DG}	Constant coefficients of DG's cost function.

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$P^{DG,Max}/Q^{DG,Max}$	Upper bound of DG's active/reactive output.
$P^{DG,Min}/Q^{DG,Min}$	Lower bound of DG's active/reactive output.
$P^{M,Max}/Q^{M,Max}$	Upper bound of active/reactive purchasing power from upstream-grid.
$P^{M,Min}/Q^{M,Min}$	Lower bound of active/reactive purchasing power from upstream-grid.
$P^{L,Max}/Q^{L,Max}$	Upper bound of active/reactive line flow.
$V^{\max}/V^{\min}$	Limitation of bus voltage.
θ	Phase difference of voltages.
P^{Load}	Prosumers' fixed load.
λ^{P}	Exchange price.
$P^{dg,Max}/P^{dg,Min}$	Active power limitation of DGs of prosumer.
a^{dg}, b^{dg}, c^{dg}	Constant coefficients of prosumer's DGs' cost function.
$P^{sto,c}, P^{sto,d}$	Upper bound rate of storage's charge/discharge.
$SOC^{\max}/SOC^{\min}$	State of charge of prosumer's storage (%).
η^{c}/η^{d}	Charge/discharge efficiency of prosumers' storage.
RR^{DG}/RR^{dg}	network/prosumer DGs' ramp rate.
P^{PV}/P^{WT}	PVs/wind turbines' output.
P^{D_0}/Q^{D_0}	Active/ reactive loads before applying CVR.
$Z^{P}/I^{P}/P^{P}$	Active coefficients of ZIP model consisted of constant impedance/ current/power.
$Z^{Q}/I^{Q}/P^{Q}$	Reactive coefficients of ZIP model consisted of constant impedance/ current/power.
λ^{M}	Nodal price.
λ^{T}	Hourly price of power.
X^{Min}/X^{Max}	Minimum/maximum of load shifting.
Q^{Cap}	Size of capacitor.
ρ^{LA}	Contribution of buses in network's loss.
P^{inj}	Injected power of generators into the bus to which they are connected.
P^{Loss}	Active loss.
V^{0}	Voltage before CVR.
λ^{LC}	value of loss of load (VOLL).
OF^{DSO}/OF^{PRO}	Objective function of DSO/prosmers.
f^{LA}/f^{PT}	Cost of loss/demand.
P^{LA}/P^{PT}	Loss allocation/power tracing.

D. VARIABLES

P^{D}/Q^{D}	Active/ reactive loads after applying CVR.
P^{DG}/Q^{DG}	Active/reactive power of generators.
P^{M}/Q^{M}	Active/reactive purchasing power from upstream-grid.
P^{L}/Q^{L}	Active/reactive power flow.
P^{pro}	Produced power of prosumer.
$P^{DSO-PRO}$	Exchanging power of DSO and prosumer.
P^{dg}	Output power of prosumer's DGs.
E	Energy level of prosumer's storage.
δ	Voltage angle.
V	Voltage magnitude.
P^{LC}	Magnitude of load curtailment.
X^{LS}	Ratio of shifted load to the original load.
$P^{Load,LS}$	Load of prosumers after CVR.

I. INTRODUCTION

Maintaining a dynamic balance between power production and consumption is key in creating future smart cities. The temporary increase in demand creates a power shortage which needs to be solved immediately to keep the network operational. Conservation voltage reduction (CVR) is a method mainly employed for reducing power consumption to reduce the supplied voltage within an acceptable boundary. Since the major part of loads is sensitive to voltage, the CVR operation can manage electricity load consumption. The traditional approach for CVR is to lower the voltage at the supplying substation by adjusting the tap positions of the on-load tap changer (OLTC) in a way that does not violate the customers' statutory restrictions [1].

Given that the main motivation for using CVR is the reduction of demand during peak load hours, CVR can be considered a solution in sustainable grids that provides more operation cost reduction, fewer greenhouse gases emission, and curtailment and shifting seasonal peak loads. Due to the deployment of DERs, prosumers, and microgrids in smart grids, it is essential to discuss the CVR's function under the new conditions.

A. LITERATURE REVIEW

A CVR operation that is enabled by a smart grid, a multi-stage, multiobjective Volt/VAR control technique has been suggested in [2]. An approach for the coordinated operation of networked microgrids (MGs), distributed energy resources (DERs), and volt-VAR control devices (VVO) to execute volt-VAR optimization is suggested in [3]. The authors' concept, while geared at conservation voltage reduction, may be expanded to address any additional VVO issues. In [4], the major goal is to provide an upgrade strategy for a microgrid by minimizing the costs associated with system upgrades, losses, peak load losses, and demand costs. CVR implantation enables the final goal to be accomplished. In [5], the coordinated allocation of battery energy storage system and soft open point incorporating demand response (DR), and conservation voltage reduction (CVR) schemes in an optimal operation. The CVR approach is suggested to be used on the electricity systems of Georgia Transmission Corporation, and Washington EMC in [6]. The number of watts and money saved are calculated by reducing the utility's peak power use. In [7], a field-validated load model-based economic model for evaluating continuous CVR's effects throughout peak and off-peak periods is proposed. In [8] the real-time component ratings and voltage-dependent characteristics of the electric loads are used to provide a peak-load management framework that will enable the DN operator to manage peak periods effectively.

The works mentioned above, although they study the impacts of CVR on economic optimization, lack investigation of the direct Impacts CVR might have on nodal pricing and electricity market operation in the presence of distributed energy resources DER.

In the following, some of the works on the implantation of DR in CVR operation are reviewed. To implement CVR when distributed energy resources like solar photovoltaic (PV) systems, energy storage systems (ESSs), and demand response programs are incorporated into distribution networks, a hierarchical look-ahead structure is offered in [9]. In [10], a methodology for calculating and evaluating the contribution of CVR to the reliability of electrical networks is studied. In particular, it predicts how energy demand will react to demand management actions taken by the electrical distribution system to lower customer demand during times of noticeably low supply-demand margins. An alternative approach to creating autonomous microgrids to reduce the power consumption of the microgrid is suggested in [11]. This approach makes use of the conservation voltage reduction idea. The Voltage Current (V-I) droop characteristic, which is intended to carry out demand side management through voltage control, is the foundation of the suggested control technique.

The mentioned works integrate DR in CVR operation but how the intertwined operations of CVR and DR in a distribution system would impact the pricing and electricity market at distribution levels, need to be further studied.

A comprehensive market/network model is needed to study the impact of CVR on the electricity market, considering the participation of DSO, DGs, prosumers, DERs, etc. The prosumers are customers who buy/sell from/to the DSO. In a market consisting of DSO and prosumers or other DERs, a market-clearing mechanism is required that considers the profits of both sides of the trade. Due to the participation of DSO and prosumers in a shared market, they act as a competitor to each other, and it is important to have fair market clearing. Bi-level programming methods are considered suitable solutions for similar problems with such conditions.

Spatial fairness in a DLMP-based bi-level transactive market is accomplished [12] by incorporating a regularization term called Jain's fairness index in the objective function. In [13], the upper-level of the bi-level approach maximizes the benefits of DSO, and the lower level tries to maximize DR aggregators' profit. A bi-level model is formulated for microgrids to participate in real-time markets of transmission-level in [14], in which the DSO and microgrid's goal is guaranteed. A bi-level programming for the dual management of an active distribution network (ADN) with virtual power plants (VPPs) is presented in [15]. A competitive electricity market for a multimicrogrid based distribution system and investigates the interactions of DSO and microgrids in the proposed models in [16]. A bi-level coordinated control model for optimizing an active distribution network with several microgrids is presented in [17]. It is concluded in [18] that by using bi-level programming in a trans-active framework, microgrids can decrease their costs by trading energy with DSO.

Although the aforementioned papers provide comprehensive solutions to their respective bi-level problems, they lack the dynamic pricing mechanism needed to investigate the impacts of CVR on the market. There are many studies for pricing energy in distribution networks; some are reviewed in the following.

The deregulation of the nations' energy markets forces market participants to adjust their operations to the new environment [19]. In [20], a methodology based on the distributional locational marginal price (DLMP) minimizes network congestion by considering network power flows is calculated. In [21], a DLMP scheme is investigated, which boosts the penetration of small-scale prosumers with an alternating direction method of multipliers (ADMM) algorithm. In [22], the iterative computation framework for DLMPs is obtained using a lossy direct-current optimum power flow. DLMP pricing is offered in [23] for an electricity-heat integrated market considering the network's status. Although mentioned papers on pricing present solid solutions to their respective problems, the gap in illustrating a direct relation between demand and prices will be filled in this paper.

B. MOTIVATIONS AND NOVELTIES

Although provided with methods suited for their investigations, the previous researches about CVR suffer from some technical and knowledge gaps that need to be addressed.

- First and foremost, the economic aspect of CVR and how it would affect the prices and local market is ignored in the mentioned papers.
- Second, the requirement is a programming plan that considers all participating agents' economic optimization and technical constraints in the network.
- The third item would be the need for an algorithm that enables the system operator to coordinate the CVR program with DR, which all participants will consider.

The novelties that this paper presents could be as follows.

- To the best knowledge of the authors of this paper, the proposed pricing and the market-clearing scheme is the first case in the field of market clearing that directly considers the effects of CVR on prices and market clearing.
- Moreover, this paper presents a decentralized bi-level market-clearing method that allows each layer to participate in the market as profitably as possible. The benefit of the introduced bi-level approach is that it allows each level to optimize its interests in the presence of different technical operations in the network.

- By placing load curtailment in the upper level and load shifting in the lower level, this paper presents solutions for the conflict of interests in DR operation in a bi-level approach. Since load curtailment is a load reduction program that pays economic incentives to the contracted consumer during power shortage periods, the DSO will operate load curtailment on its operation to guarantee its financial goals. Allowing the load-shifting program to be operated more dynamically by lower-level players will be financially beneficial for all players in response to load shortage.

The main contributions of this paper are highlighted as:

- An energy market proposed to utilize an exclusive pricing scheme based on loss allocation and power tracing, which investigates the economic features of the grid besides technical issues that come from the use of CVR. The effect of CVR on changing market prices is investigated.
- To ensure that the proposed methods are financially fair and ultimately consider all technical constraints and objectives of agents, a bi-level operation within the network operation is proposed. The proposed bi-level programming is based on an iterative method considering CVR and DR programs.
- The load shifting and load curtailment subprograms of DR are placed in an appropriate position for bi-level programming. Such placement is for coordinating the operation of DR with CVR to cut the network's demand under power shortage periods optimally.
- This paper presents the concept of price to voltage sensitivity under CVR. Investigation of price to voltage sensitivity of power generation units allows the system operators to plan their activities with improved foresight under CVR operation.

Table 1 is presented to provide a comparison between this paper and some of the papers studied in the review literature.

The following outlines how this paper is organized. The overall model of the article is detailed in section II. In the problem formulation, Section III examines the associated problem in great depth. Section IV discusses the analyzed examples and their numerical outcomes. The conclusions drawn from this investigation are discussed in section V, the last part of the paper.

II. MODEL DESCRIPTION

For many years the shortage of electricity production during peak hours or seasonal power shortages has caused many problems. The application of CVR and demand response programs are two main solutions to the temporary power shortage problem. To reduce customer demand, CVR is the intentional reduction of customer voltages at the lower end of the acceptable range. The CVR operation is usually performed using OLTC to change the transformer's output voltage without disturbing the power supply. This paper studies the application of CVR and DR in distribution systems and how that would affect the electricity market. The usage of loss allocation and power tracing in the pricing mechanism enables the DSO to calculate the change in price caused by CVR. Since the proposed pricing mechanism is a dynamic pricing method, a change in demand will noticeably change the trading power price. DSO calculates the cost of energy by allocating power supply costs to each nodal costumers. The share of generation units in customers using power tracing is discovered.

The calculated power contributions are fed into each generation unit's cost function to determine the cost of power supply to each customer by each generation unit. Each customer's individual expenditures for each generation unit are added together to get the overall energy cost of each customer. Divide the entire energy cost by the total consumed power to get the power exchange price. Upstream-grid, DSO, DGs, fixed loads, prosumers, and curtailable loads make up the market structure of this study, as shown in Fig. 1. The DSO procures the power needs from the upstream grid and DGs. The prosumers have the ability to purchase/sell energy from/to DSO. The loads participating in the load curtailment program will curtail their demand up to a certain amount.

In some circumstances, such as over-voltage, congestion, and supply shortage, DSO would consider the load curtailment and will decide which load and how much power should be curtailed. According to the regulated contract, such loads will be prioritized to curtail their demand by assessing DSO. The prosumers also can participate in the DR program by shifting some percentage of their demand from peak demand hours to other time slots.

TABLE 1. Literature review.

References	CVR	DR	Decentralized optimization	Pricing and market
[2]	Yes	No	No	No
[3]	Yes	No	No	No
[4]	Yes	No	No	No
[5]	Yes	Yes	No	No
[6]	Yes	No	No	No
[7]	Yes	Yes	No	No
[8]	Yes	Yes	No	No
[9]	Yes	Yes	No	No
[10]	Yes	Yes	No	No
[11]	Yes	No	Yes	No
[20]	No	No	Yes	Yes
[21]	No	Yes	Yes	Yes
[22]	No	Yes	No	Yes
[23]	No	No	No	Yes
Proposed paper	Yes	Yes	Yes	Yes

III. PROBLEM FORMULATION

Related equations and problems to the proposed model are discussed in this section, which investigates the model's voltage-dependent loads and bi-level programming.

A. LOAD MODEL

Since the concept of CVR operation is based on reducing energy by reducing the voltage, it is important to have an accurate load model. The studies have investigated the relationship between voltage and consumption amount and

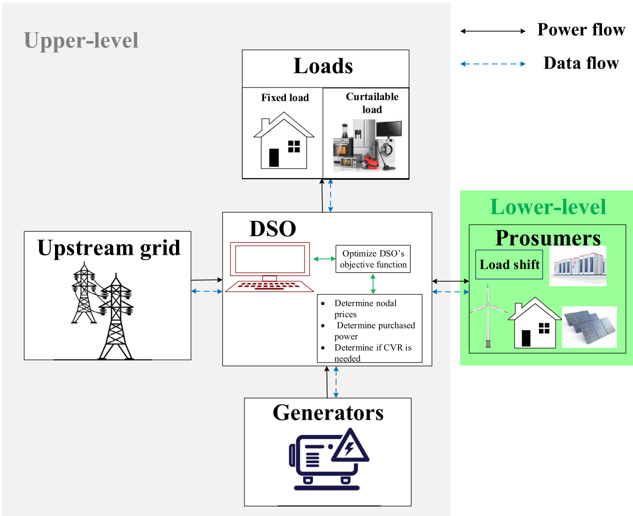

FIGURE 1. Market structure.

concluded that load could be modeled as a quadratic ZIP equation. The ZIP load model has coefficients for constant impedance, constant current, and constant power consumers depending on the load's type and magnitude. The constant coefficients relay the sensitivity of the load toward changes in its voltage. The ZIP load model for active/reactive loads is expressed as:

$$P_{m,t,k}^{D} = P_{m,t,k}^{D_0} \begin{bmatrix} Z_{m,t,k}^{P}\left(\frac{V_{m,t}}{V_{m,t,k}^{0}}\right)^2 \\ +I_{m,t,k}^{P}\left(\frac{V_{m,t}}{V_{m,t,k}^{0}}\right) \\ +P_{m,t,k}^{P} \end{bmatrix} \tag{1}$$

$$Z_{m,t,k}^{P} + I_{m,t,k}^{P} + P_{m,t,k}^{P} = 1 \tag{2}$$

$$Q_{m,t,k}^{D} = Q_{m,t,k}^{D_0} \begin{bmatrix} Z_{m,t,k}^{Q}\left(\frac{V_{m,t}}{V_{m,t,k}^{0}}\right)^2 \\ +I_{m,t,k}^{Q}\left(\frac{V_{m,t}}{V_{m,t,k}^{0}}\right) \\ +P_{m,t,k}^{Q} \end{bmatrix} \tag{3}$$

$$Z_{m,t,k}^{Q} + I_{m,t,k}^{Q} + P_{m,t,k}^{Q} = 1 \tag{4}$$

B. BI-LEVEL OPTIMIZATION FOR MARKET-CLEARING

Due to the presence of DSO and prosumers in this market which have profit objectives that put them in contrast with each other, a clearing mechanism that considers both parties' objectives is needed. This paper uses the bi-level programming method to ensure the market-clearing mechanism is fair to both participants.

1) UPPER-LEVEL OPTIMIZATION: OPTIMIZATION OF DSO's COST

The cost minimization of DSO is represented in the upper level, which is subjected to the network's technical constraints.

The objective function for minimizing the costs of DSO can be presented as:

$$\begin{aligned} &Min\ OF^{DSO} \\ &= \sum_{t\in\Gamma_T}\sum_{c\in\Gamma_C}\lambda_t^T P_{c,t,k}^{M} + \sum_{t\in\Gamma_T}\sum_{i\in\Gamma_P}\lambda_{i,t,k}^{P} P_{i,t,k}^{DSO-PRO} \\ &\quad + \sum_{t\in\Gamma_T}\sum_{g\in\Gamma_{DG}}\left(a_g^{DG}\left(P_{g,t,k}^{DG}\right)^2 + b_g^{DG}P_{g,t,k}^{DG} + c_g^{DG}\right) \\ &\quad + \sum_{t\in\Gamma_T}\sum_{m\in\Gamma_{LC}}\lambda^{LC}P_{m,t,k}^{LC} \end{aligned} \tag{5}$$

The first term presents the cost of purchasing power from the upstream grid. The second term of the upper level expresses the cost/profit from buying/selling energy to prosumers. The third term indicates the cost of generators in the network. The last term represents the cost of load curtailment in the DR program.

2) NETWORK's CONSTRAINTS

The nodal power balancing on each bus of the network is expressed as:

$$\begin{aligned} &\sum_{c\in\Omega_C} P_{c,t,k}^{M} + \sum_{g\in\Omega_{DGm}} P_{g,t,k}^{DG} + \sum_{i\in\Omega_{Pm}} P_{i,t,k}^{DSO-PRO} \\ &\quad = P_{m,t}^{D} - P_{m,t}^{LC} + \sum_{n\in\Omega_{Bmn}} P_{m,n,t,k}^{L} \end{aligned} \tag{6}$$

$$\begin{aligned} &\sum_{c\in\Omega_C} Q_{c,t,k}^{M} + \sum_{g\in\Omega_{DGm}} Q_{g,t,k}^{DG} + Q_{m,t,k}^{Cap} \\ &\quad = Q_{m,t}^{D} + \sum_{n\in\Omega_{Bmn}} Q_{m,n,t,k}^{L} \end{aligned} \tag{7}$$

Maximum and minimum active/reactive power generation of DGs are limited as:

$$P_g^{DG,Min} \le P_{g,t,k}^{DG} \le P_g^{DG,Max} \tag{8}$$

$$Q_g^{DG,Min} \le Q_{g,t,k}^{DG} \le Q_g^{G,Max} \tag{9}$$

The purchased active/reactive power from upstream-grid are limited as:

$$P_c^{M,Min} \le P_{c,t,k}^{M} \le P_c^{M,Max} \tag{10}$$

$$Q_c^{M,Min} \le Q_{c,t,k}^{M} \le Q_c^{M,Max} \tag{11}$$

Active/reactive power flow of the lines is calculated subject to their limitations as:

$$\begin{aligned} P_{m,n,t,k}^{L} &= \frac{V_{m,t,k}^2}{Z_{m,n}}\cos\left(\theta_{m,n}\right) \\ &\quad - \frac{V_{m,t,k}V_{n,t,k}}{Z_{m,n}}\cos\left(\delta_{m,t,k} - \delta_{n,t,k} + \theta_{m,n}\right) \end{aligned} \tag{12}$$

$$-P_{m,n}^{L,Max} \le P_{m,n,t,k}^{L} \le P_{m,n}^{L,Max} \tag{13}$$

$$\begin{aligned} Q_{m,n,t,k}^{L} &= \frac{V_{m,t,k}^2}{Z_{m,n}}\sin\left(\theta_{m,n}\right) \\ &\quad - \frac{V_{m,t,k}V_{n,t,k}}{Z_{m,n}}\sin\left(\delta_{m,t,k} - \delta_{n,t,k} + \theta_{m,n}\right) \end{aligned} \tag{14}$$

$$-Q_{m,n}^{L,Max} \le Q_{m,n,t,k}^{L} \le Q_{m,n}^{L,Max} \tag{15}$$

The ramp rate of the network's DGs is limited as:

$$\left|P^{DG}_{g,t,k} - P^{DG}_{g,t-1,k}\right| \leq RR^{DG}_{g} \tag{16}$$

The voltage and angel of the slack bus are set as:

$$\left(V_{c,t,k}, \delta_{c,t,k}\right) = (1, 0) \tag{17}$$

The magnitude of the voltage of buses is limited as:

$$V^{Min} \leq V_{m,t,k} \leq V^{Max} \tag{18}$$

3) LOAD CURTAILMENT

Consumers that have the ability to curtail their loads in exchange for economic incentives, participate in the DR program. Other consumers' loads do not change after the DR program. The curtailable Load's limitation in load reduction is expressed as:

$$0 \leq P^{LC}_{m,t,k} \leq P^{D}_{m,t,k} \tag{19}$$

4) PRICING MECHANISM

It is needed to gain loss allocation and power tracing results to start the pricing process. In power tracing contribution of each electricity-producing unit to each load is calculated. The power tracing method used in this paper is based on the combination of circuit theory and the concept of fair distribution of game theory. The same techniques are used for loss allocation calculation. Both the loss allocation and power tracing are based on Aumann-Shapley's calculation. Prices are separated into energy prices and the price of lost power. For energy pricing, the first energy cost for each load is calculated. The share of power-producing units in loads is calculated by using its cost function to obtain the imposed costs to producers. Imposed cost to each electricity producer in each load is aggregated with other producers' costs to obtain the total cost of each load. The total cost is divided by the consumed power to gain the energy price. The overall loss cost is estimated in loss pricing by subtracting received power from generated power of each unit and combining the results. The allocated loss is divided by the total loss of the network to gain the share of buses in the total loss. The loss share of buses in the total loss is multiplied by the total loss cost to obtain the loss cost generated by each bus. In the price formulation, u is the index of the set of power generation units (Θ_G), which consists of the upstream grid (Γ_C), network generators (Γ_{DG}), and prosumers (Γ_P).

The nodal price for market-clearing is stated as:

$$\lambda^{M}_{m,t,k} = \sum_{u\in\Theta_G} \frac{\rho^{LA}_{m,t,k}}{P^{Loss}_{t,k}} f^{LA}_{u,t,k} + \sum_{u\in\Theta_G} \frac{f^{PT}_{m,u,t,k}}{P^{D}_{m,t}} \tag{20}$$

$$f^{LA}_{u,t,k} = \left(a^{G}_{u} P^{LA}_{u,t,k} + b^{G}_{u}\right) P^{inj}_{u,t,k} + c^{G}_{u}\left(\frac{P^{LA}_{m,t,k}}{\sum_{m\in\Gamma_B} P^{D}_{m,t,k} + P^{Loss}_{t,k}}\right) \tag{21}$$

$$f^{PT}_{m,u,t,k} = \left(a^{G}_{u} P^{PT}_{m,u,t,k} + b^{G}_{u}\right) P^{inj}_{u,t,k} + c^{G}_{u}\left(\frac{P^{PT}_{m,u,t,k}}{\sum_{m\in\Gamma_B} P^{D}_{m,t,k} + {}^{Loss}_{t,k}}\right) \tag{22}$$

The first term of (20) presents the loss pricing procedure, and the second term presents the pricing for traded energy. The total price for each bus is gained by aggregating such two prices. The loss pricing procedure of calculating attributed loss cost is expressed in more detail in (21). The cost related to power consumption is presented in (22). The process and formulations of used power tracing and loss allocation are discussed in more detail in [24] and [25], respectively.

The utilized pricing method is explained in more detail in [26].

5) LOWER-LEVEL: OPTIMIZATION OF PROSUMERS' PROFITS

The prosumer's profit is maximized in the lower level section of the problem. The technical constraints of prosumers represent the constraints of the lower level.

$$\begin{aligned} Max\ OF^{PRO} &= \sum_{t\in\Gamma_T}\sum_{i\in\Gamma_P} \lambda^{P}_{i,t,k} P^{DSO-PRO}_{i,t,k} \\ &\quad - \sum_{t\in\Gamma_T}\sum_{j\in\Pi_{DG}} \left(a^{dg}_{j}\left(P^{dg}_{j,t,k}\right)^2 + b^{dg}_{j} P^{dg}_{j,t,k} + c^{dg}_{j,t}\right) \end{aligned} \tag{23}$$

The profit/cost from selling/buying energy to/from DSO presents the first term of the lower level. The operation cost of prosumers' DGs is represented in the second term.

6) LOAD SHIFTING

Under the load shifting program, prosumers are able to shift a certain portion of their load's from a one-time slot to another one. The changes in prosumers' load and its impact on power exchange between prosumer and DSO are presented as:

$$P^{Load,LS}_{i,t,k} = X^{LS}_{i,t,k} P^{Load}_{i,t,k} \tag{24}$$

The limitation for load shift's magnitude is expressed as:

$$X^{Min}_{i} \leq X^{LS}_{i,t} \leq X^{Max}_{i} \tag{25}$$

7) TECHNICAL CONSTRAINTS

Technical aspects of prosumers are important factors for accurately market-clearing of the network. The relations of different components of prosumers are stated in the following.

Power production of prosumers' DGs is limited as:

$$P^{dg,Min}_{j} \leq P^{dg}_{j,t,k} \leq P^{dg,Max}_{j} \tag{26}$$

The ramp rate of DGs of prosumers is limited as:

$$\left|P^{dg}_{j,t,k} - P^{dg}_{j,t-1,k}\right| \leq RR^{dg}_{j} \tag{27}$$

Charge /discharge rates of storages are limited as:

$$0 \leq P^{sto,+}_{i,t,k} \leq P^{sto,c}_{i} \tag{28}$$

$$0 \leq P^{sto,-}_{i,t,k} \leq P^{sto,d}_{i} \tag{29}$$

Equation (30) presents that storages cannot charge and discharge in the same time interval.

$$P_{i,t,k}^{sto,+} P_{i,t,k}^{sto,-} = 0 \tag{30}$$

The energy in storage in each time interval is related to the previous time interval's energy is presented as:

$$E_{i,t,k} = E_{i,t-1,k} + \eta_i^c P_{i,t,k}^{sto,+} \Delta - \frac{1}{\eta_i^d} P_{i,t,k}^{sto,-} \Delta \forall i \in \Omega_P, \forall t \in \Omega_T, \forall k \tag{31}$$

The stored energy level in storage is:

$$E_i^R SOC_i^{\min} \leq E_{i,t,k} \leq E_i^R SOC_i^{\max} \tag{32}$$

The total power production of prosumers is composed as:

$$P_{i,t,k}^{pro} = \sum_{j \in \Psi_{DGi}} P_{j,t,k}^{dg} + P_{i,t,k}^{WT} + P_{i,t,k}^{PV} + P_{i,t,k}^{sto,-} - P_{i,t,k}^{sto,+} \tag{33}$$

The exchanging power from prosumer to DSO is equal as:

$$P_{i,t,k}^{DSO-PRO} = P_{i,t,k}^{pro} - P_{i,t}^{Load,LS} \tag{34}$$

Information about the price-to-voltage sensitivity of power production units could be advantageous for better planning of networks under CVR operation. The price-to-voltage sensitivity data lets the network operator more perspicuously predict the behavior of power production units.

$$CVR_{i,t}^{\lambda-V} = \frac{\Delta\lambda_{i,t}^{P} / \lambda_{i,t}^{P,0}}{\Delta V_{i,t} / V_{i,t}^{0}}; \ \Delta\lambda_{i,t}^{P} = \lambda_{i,t}^{P,CVR} - \lambda_{i,t}^{P,0} \tag{35}$$

$CVR_{i,t}^{\lambda-V}$ expresses the sensitivity of price toward changes in voltage under CVR. $\lambda_{i,t}^{P,CVR}/\lambda_{i,t}^{P,0}$ are prices under/without CVR.

C. SOLUTION METHODOLOGY

The suggested pricing and market clearing flowchart are presented in Fig. 2. The process begins with DSO running the OPF program with initial input data considering CVR and load curtailments in its objective function and constraints. The network's load shortage is tackled after DSO economically and technically fixes the network's problems. The load reduction programs will begin if there is a load shortage in the network. The proposed load reduction programs are CVR, load curtailments, and load shift which all are done in an economically optimal procedure. The CVR and load curtailment are executed by DSO, which is the upper level in this paper. Prosumers are responsible for the load shifting, which is the lower level of the problem. The CVR operation for load reduction continues until voltage limit conditions are violated, the operation ceases, and the pricing operation begins. If there is a power shortage after CVR operation, the load curtailment program will be operated. After CVR and demand response programs, the network load demands will be updated, and the pricing scheme will begin based on new demands. The prices for customers are constituted with loss and energy prices. Prices will be calculated and sent to prosumers, who will deploy their production units based on their objective function, considering load shift if it suits them. When prosumers determine their power exchange levels with DSO, the network's status and power flow will be updated, and the whole process will be repeated. The process will continue until there is no change in exchanged power in two consecutive iterations, where the required data will be extracted.

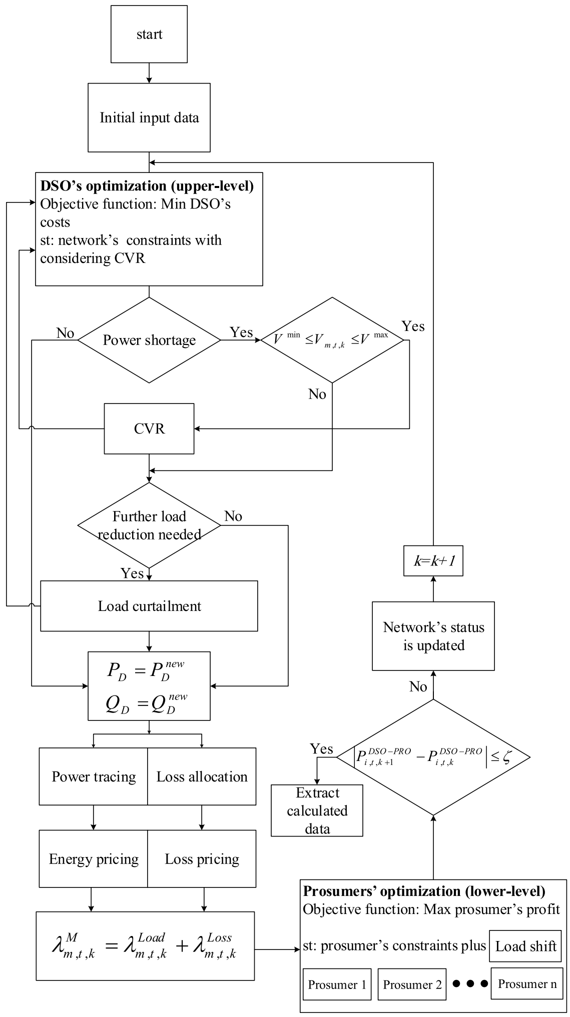

FIGURE 2. Flowchart of bi-level market-clearing under CVR and DR operations.

IV. NUMERICAL ANALYSIS

Four case studies are considered for testing and studying the proposed model's performance. A modified IEEE 33-bus system is selected for the simulation of case studies. The test system is presented in Fig. 3, which consists of four prosumers with various power production units and loads participating in the DR program. The simulations are carried out through GAMS and MATLAB programs to obtain the presented results of case studies.

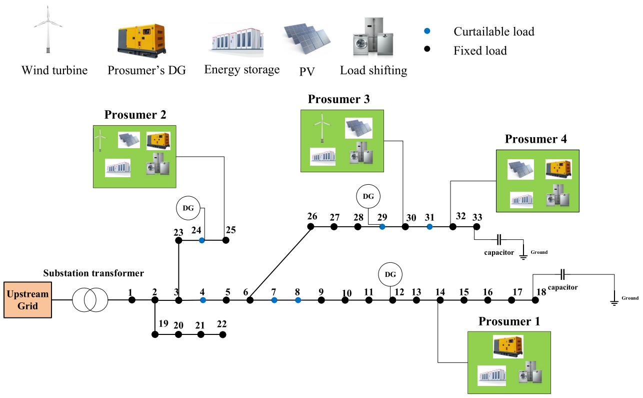

FIGURE 3. Diagram of modified IEEE 33-bus test system.

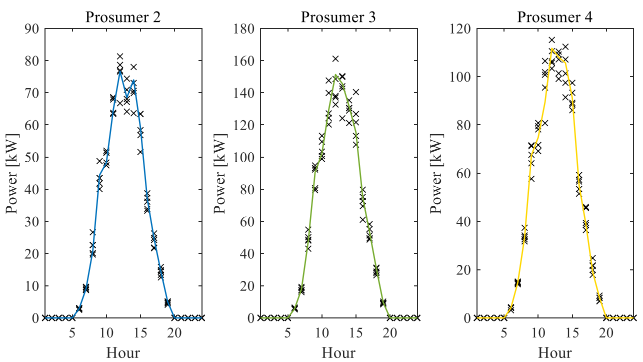

FIGURE 4. The power output of PVs.

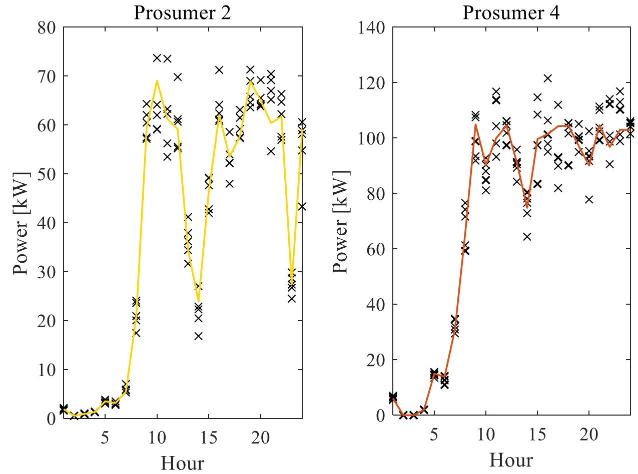

FIGURE 5. The power output of wind turbines.

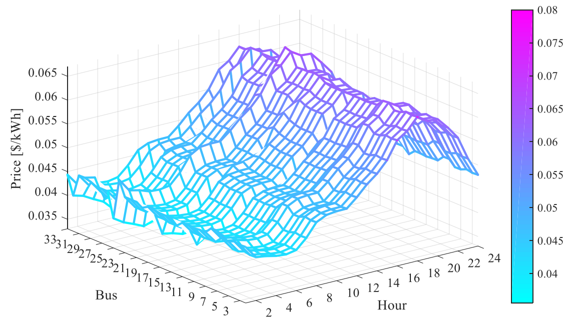

FIGURE 6. Nodal price in case 1.

A. UNCERTAINTY OF RENEWABLE ENERGY RESOURCES

The power output of renewable energy resources depends on many variable conditions, such as weather conditions which cause them to have uncertain power output patterns. The stochastic method is chosen to simulate the uncertainty of renewable energy resources by implanting five scenarios from the related probability density function (PDF) with their respective probability chances. The power output of PVs and wind turbines and their expected value are calculated by averaging the values of five scenarios multiplied by their respective probability weight. The output of renewable energy resources is presented in Figs. 4 and 5.

B. CASE STUDIES

Four different case studies are investigated in this section, in which the first case study is the base case without considering CVR and DR operations. The CVR program is applied to the market operation in the second case study. The impact of capacitor placement is discussed in case three. Finally, the impact of the joint operation of CVR and DR is discussed in case four.

1) CASE 1: BASE CASE WITHOUT CVR

In case 1, the base conditions are created to study the proposed formulation. Furthermore, the base system is used to compare and investigate how the behavior of the system would change if different conditions were imposed on the system. The price of exchanging power at each bus is presented in Fig. 6. In the first 6 hours, the prices slightly decline, then increase until they reach their peak amounts at hours 17-18. In addition, the prices are significantly different on buses 7-8 and 24-25. Both such behaviors are due to having a dynamic pricing method. Since the proposed pricing mechanism is based on power tracing, price, and load have direct relation; when the demand increases, the prices also increase. Hours 17-18 are peak demand hours; hence the prices are maximum in those hours. Since buses 7-8 and 24-25 have a higher load profile, their prices are also higher. As presented in Fig. 7, the prosumers in hours 1-6 prefer to purchase power from DSO when prices have the lowest values. But, in hours 17-18, since prices are higher, prosumers produce power at the highest levels, sell power at the highest, or purchase at the lowest levels. Prosumer 4 has negative exchanging power during the 24 hours due to its larger load than its production capacity. The storages of prosumers charge their energy levels from hour 1 to hour 6, where they reach their maximum capacity. As presented in Fig. 8, storages store their energy levels till hour 16, when they begin to discharge their energy during the high-price hours until they discharge all of their energy. The voltage profile of the network is illustrated in Fig. 9.

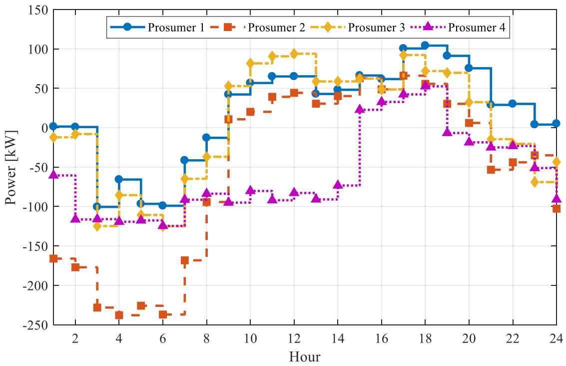

FIGURE 7. Exchanging power between prosumers and DSO in case 1.

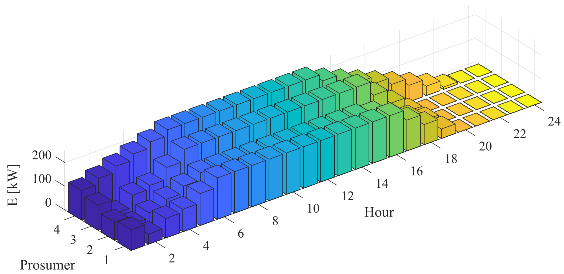

FIGURE 8. Energy levels of storage in case 1.

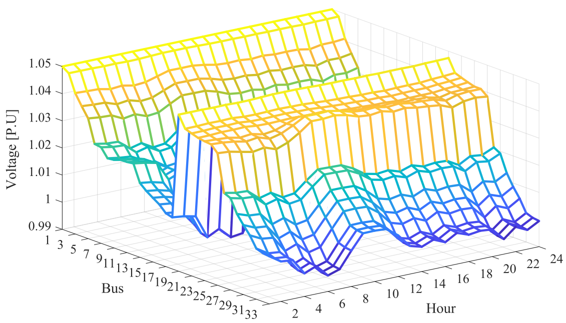

FIGURE 9. Voltage profile of the network in case 1.

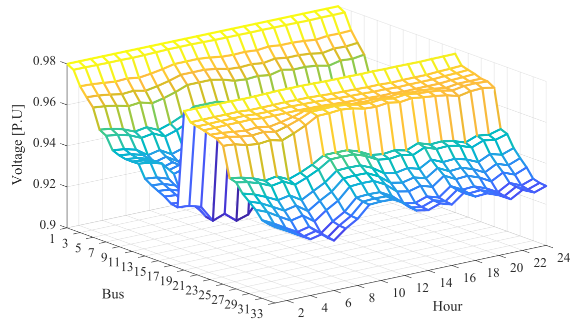

FIGURE 10. Voltage profile of network in case 2.

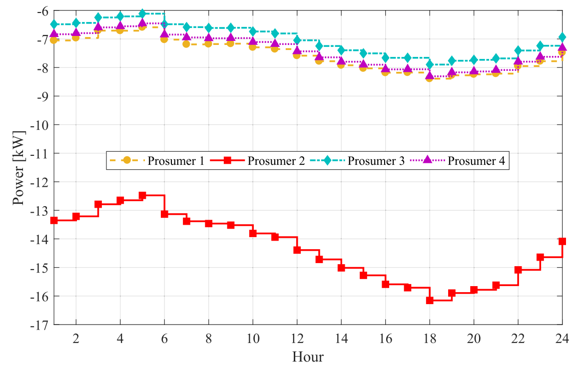

FIGURE 11. Load change in case 2 compared to case 1.

2) CASE 2: TEST SYSTEM WITH CVR

The main purpose, in this case, is to decrease the grid's loads in 24 hours. It is assumed that there is a high seasonal demand for power, and operators try to reduce the load in both peak and off-peak load hours. DSO subsequently tries to lower the purchasing power from the upstream grid as much as possible by implanting CVR, which is assumed is under pressure to provide power. In case 2, the slack bus voltage is decreased from 1.05 P.U to 0.98 P.U, as presented in Fig. 10. CVR operation is done by changing the tap of the upstream grid's transformer, decreasing the voltage of the connecting bus to the upstream grid. Since loads of the network depend on their voltage with their respective ratio, the load of buses will also decrease, as represented in Fig 11. The coefficients of load and voltage relativity can be found in [27]. The results of this case study are compared to case 1 to evaluate the influence of CVR on price and prosumer exchange power. As presented in Fig. 12, the prices will change due to being dynamic and dependent on demand. The prices will generally decrease due to the reduction of demand caused by CVR. The decline of the load of buses and the price of exchanging power will change the exchanging power between the DSO and prosumers, as expressed in Fig. 13. Since prosumers have a decreased load at steady levels, their sold power generally increases, but the exchanging power diagram changes depending on the price. The sudden decrease/increase of exchanging power of Prosumer 3 in hour 5 and hour 7 is due to the charge/discharge of its storage which is planned following the change in price signals. Fig. 14 presents prosumers' price to voltage sensitivity. As presented in Fig. 14, generally, across the different hours, sensitivity is constant except for peak hours, where the prices for prosumers' power exchange are more sensitive to changes in the voltage. The price sensitivity of prosumers depends on their load type and magnitude. The DSO cost and prosumers' profits are presented in Table 2. It is noted that the DSO's cost decreases by 3.9% from 4245$ to 4078.4$, and the prosumers' profit increases.

3) CASE 3: TEST SYSTEM WITH CVR AND CAPACITOR

After supplementing the CVR program to the network, the voltage of certain buses might decline to critical lows, which may harm the electric hardware. Placing capacitors in certain locations is a solution to this problem. If capacitors are implanted in the network, this case explores how changes in

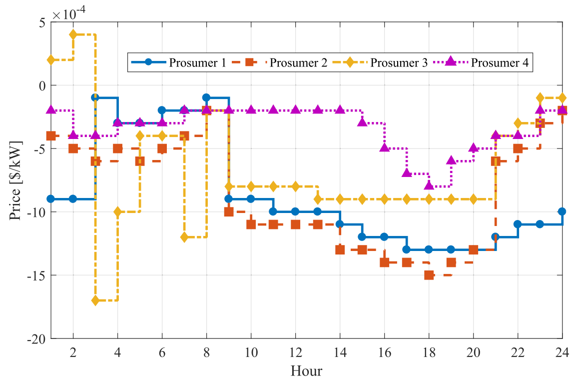

FIGURE 12. Power exchange price change between case 1 and case 2.

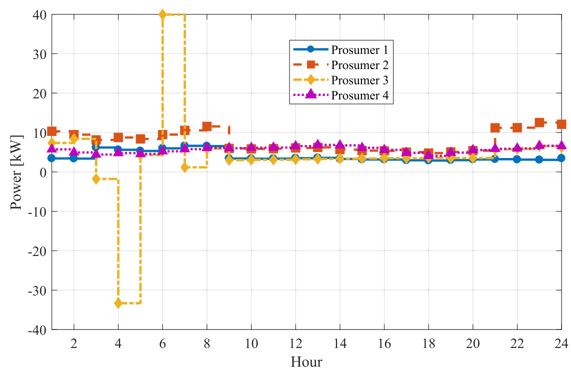

FIGURE 13. Change of power exchange between prosumers and DSO in case 2 from case 1.

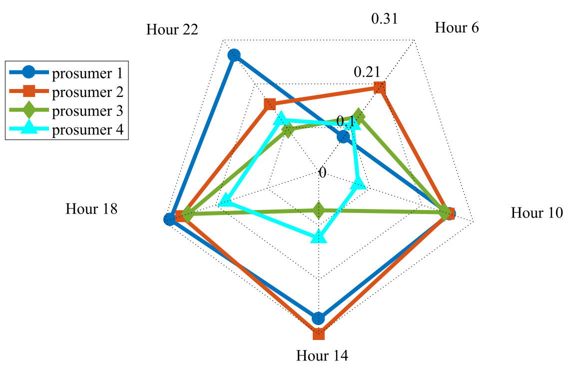

FIGURE 14. Price to voltage sensitivity of prosumers in case 2.

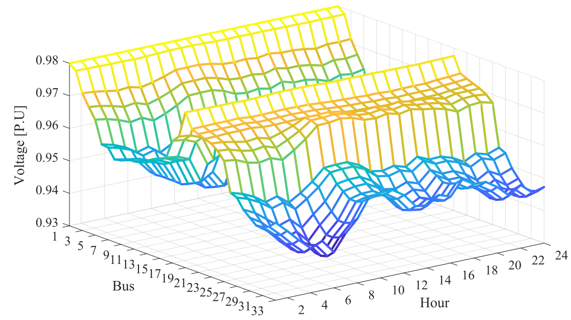

FIGURE 15. Voltage profile of the network in case 3.

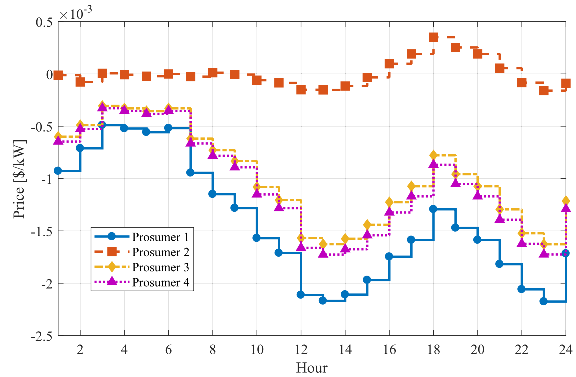

FIGURE 16. Power exchange price change between case 3 and case 2.

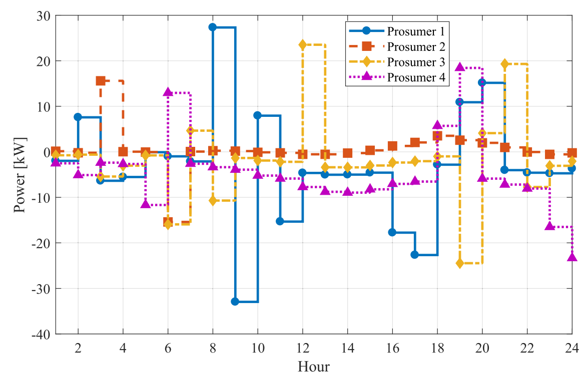

FIGURE 17. The power exchange between prosumers and DSO changes in case 3 from case 2.

network properties would affect nodal pricing and prosumer behavior. The results of this case are compared with the results of case 2. In this case, two capacitors with the ratings of 300 and 350 kVAR are connected to the network through bus 18 and bus 33, as presented in Fig. 3. Placing capacitors in bus 18 and bus, 33 increases the voltage in the respective buses and nearby buses from 0.92 P.U to 0.945 P.U and 0.91 P.U to 0.93 P.U, respectively, as presented in Fig. 15. The load of the network due to capacitor placement further decreases, as evident in Fig. 24. As a result of more load decrease, prices generally decrease as represented in Fig. 16. Prosumers change their behavior on the basis of different conditions which are applied to them. Prosumers 1, 3, and 4, due to a decrease in their power, exchange prices generally decrease/increase their sold/purchased power, as presented in Fig. 17. The exchange power price of prosumer 2 generally increases compared to case 2, which causes the produced to increase power production of the prosumer. As presented in Fig. 18, adding capacitors increases the price to voltage sensitivity at all hours, especially in peak demand hours. The enhancement of price to voltage sensitivity, as displayed in other discussed results, causes the prosumers to behave more dynamically. DSO costs decrease and prosumers' profit increases compared to case 2.

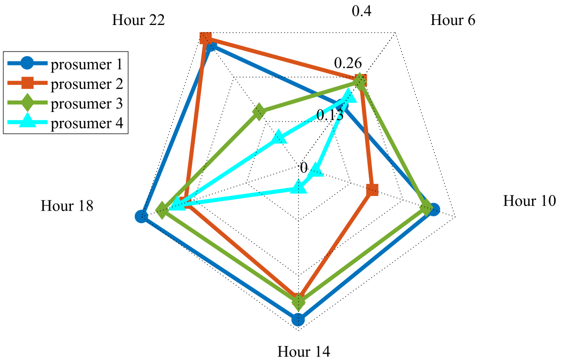

FIGURE 18. Price to voltage sensitivity of prosumers in case 3.

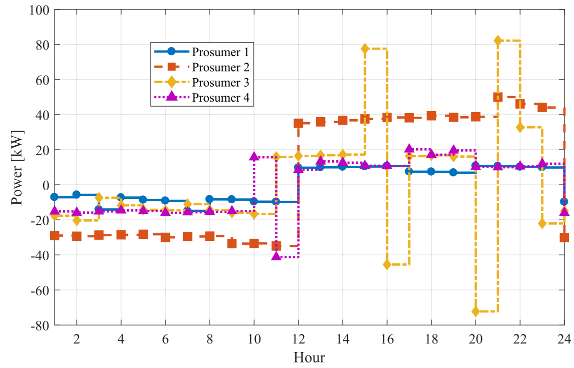

FIGURE 21. Change in exchanged powers of prosumers and DSO in case 4 compared to case 3.

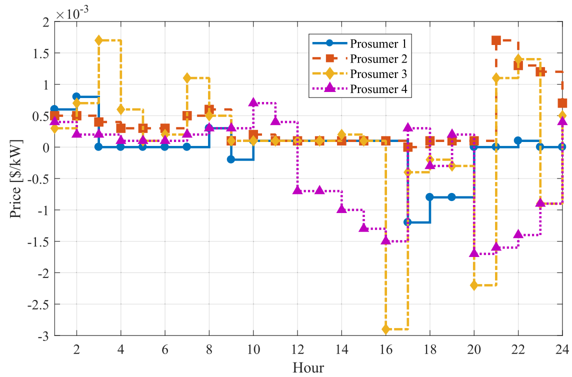

FIGURE 19. Power exchange price change between case 4 and case3.

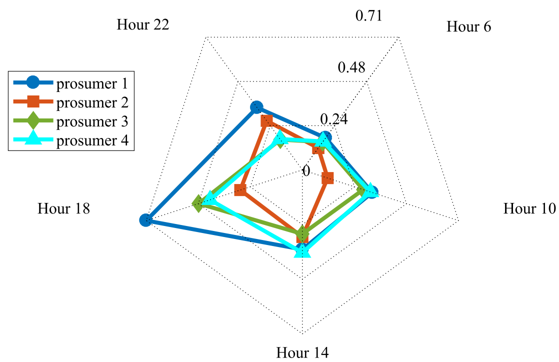

FIGURE 22. Price to voltage sensitivity of prosumers in case 4.

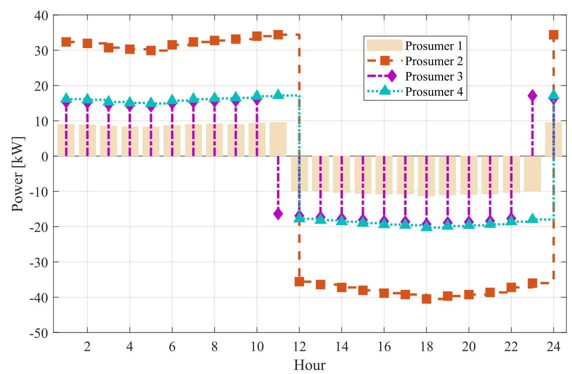

FIGURE 20. Change in loads of prosumers between case 4 and case 3.

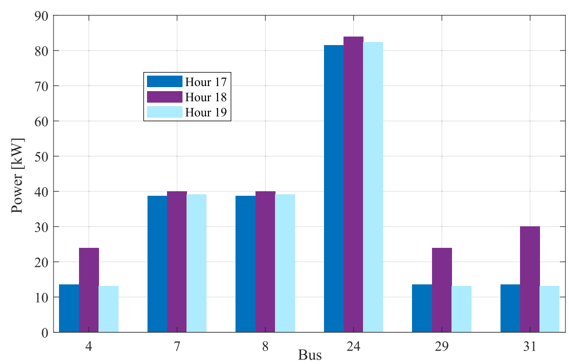

FIGURE 23. Load curtailment in case 4.

TABLE 2. Cost of DSO and profits of prosumers in each case in 24 hours ($).

Entity	Case 1	Case 2	Case 3	Case 4
DSO	4245	4078.4	4075.5	4048.5
Prosumer 1	-37.61	-29.9	-30.6	-28.75
Prosumer 2	-223.62	-206.73	-206.22	-197.94
Prosumer 3	-89.29	-81.36	-80.7	-79.49
Prosumer 4	-172.72	-163.75	-163	-159.67

4) CASE 4: TEST SYSTEM WITH DR AND CVR

This case investigates the impacts of implying DR programs on systems that already have CVR programs. In this case, it is determined that prosumers could shift up to 10% of their loads in-between hours. Also, there is an extreme load shortage in hours 17-19, so DSO will be forced to run a load curtailment program. By deploying the DR program, prosumers shift their loads to be able to sell or buy power in hours that are more beneficial to them. As visualized in Fig. 20, the prosumers shift their load from hours 12-24 to hours 1-12, enabling them to sell more power at peak price hours to increase profits, as illustrated below in Fig. 21. The DR impacts the prices in a way that hours 16-21 will mostly decrease and generally increase within hours 1-12, as presented in Fig. 19. The exchanging power between prosumers and DSO following the load shifts will increase in

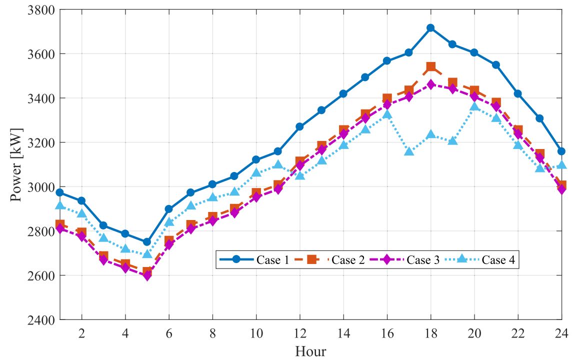

FIGURE 24. Total load of the network in each case.

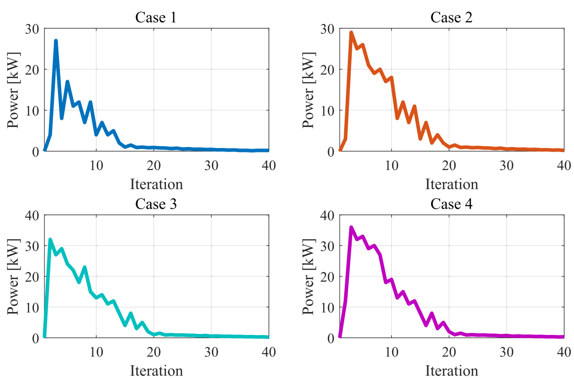

FIGURE 25. Convergence of exchanging power for prosumer 2 in each case.

TABLE 3. Generation in 24 hours (kW).

Entity	Case 1	Case 2	Case 3	Case 4
Upstream-grid	37680	34058	33950	33240
DG 1	7200	7280	7300	7400
DG 2	9600	9712	9730	9800
DG 3	7200	7280	7300	7350

hours 12-24 and will be lowered in hours 1-12. The amounts of load curtailments of buses are shown in Fig. 23. For a complete investigation of the impacts of each case, the total profits of prosumers and the cost of the DSO are presented in Table 2. The power generation of the upstream grid and the network's DGs are presented in Table 3 for a more detailed studying of each case. It should be mentioned that the data presented in table 3 is for the aggregated amount of power production in 24 hours, while data in Figs are for each time interval separately. It is depicted in table 3 that in each case, the purchasing power from the upstream grid decreases, which is in line with the purposes of the CVR and DR implantations. The network's total loads of each case are represented in Fig. 24. According to Fig. 22, the price to voltage sensitivity significantly increases, specifically in peak hours, due to DR programs, which decrease the network's and prosumers' load. The load reduction increases the power production capacity of prosumers, allowing them to react more agilely to technical changes in the network. DR programs increase the profits of prosumers and lower the costs of DSO as represented in Table 2. The convergence of exchanging power for prosumer 2 in each case as an example is illustrated in Fig. 25. From Fig. 25, it could be concluded that the presented model presents feasible solutions for raised problems in this paper.

V. CONCLUSION

This paper investigates the economic and technical effects of CVR and DR programs in distribution networks. The comprehensive market and the technical scheme proposed in this paper use a pricing mechanism directly influenced by the network's voltage and power flow technical issues. Case 1 is considered to be the base case. In case1, prices of exchanging power have a direct relation with load demand, and the exchange power between the prosumers and DSO follows the price signal. In case 2, the CVR operation is applied to the network to reduce load consumption. The prices in case 2 decrease due to load reduction because the load consumption directly influences them. Since the prices of power exchange are decreased, it is expected that prosumers will decrease their exported power to the network but slightly increase their sold power. The increase in exported power from the prosumers to DSO is due to demand reduction, which frees up their power exchange capacity. In case 3, the effects of capacitor placement in critical voltage points of the network are studied. The capacitor placement improves the network's voltage profile, which increases the load reduction in the network. Case 4 indicates the simultaneous use of DR and CVR helps with load reduction in extreme cases of power shortage. It is also noted that the appropriate placement of load shifting and load curtailment in their suitable position in bi-level programming ensures the economic interests of both the DSO and prosumers. Placement of the load shift program in the prosumers' level of programming in a market-clearing not only decreases the load in peak load hours but also, is economically beneficial for prosumers, increasing their overall profits by 3%. DSO having the task of load curtailment allows it to manage the technical and economic aspects more dynamically in the case of DR operation, decreasing its cost by 4.63%. Capacitor placement and DR programs increase the profits of prosumers and decrease the costs of DSO. The CVR operation decreases the overall load of the network by 4.75%, from 77551 kW to 73870 kW in 24 hours. The capacitor placement and DR programs further decrease the load by 5.46% and 6%, respectively, demonstrating the proposed model's ability to help develop sustainable cities. Furthermore, prosumers' price to voltage sensitivity shows that prices are more sensitive in peak demand hours. The obtained results could be used for investigating the change in DERs behavior using the CVR in future studies.

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