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A New Framework for Mitigating Voltage Regulation Issue in Active Distribution Systems Considering Local Responsive Resources

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ABSTRACT Recently, renewable energy sources (RESs) have increasingly being integrated into the power grids as a result of environmental and governmental perspectives. In this regard, the installation of RESs as potential power sources in active distribution systems would benefit the grid by decreasing the power losses, as well as addressing the fossil fuel shortages, and their environmental aspects. Nevertheless, the high-level integration of RESs as well as the development of distributed formations in local systems could challenge the reliable operation of the grid. In this context, conventional approaches could not optimally mitigate the regulation-voltage issue; therefore, utilities have to exploit the scheduling of local responsive sources to address the regulation-voltage issue in systems with high-level penetration of RESs. Consequently, the offered scheme in this paper enables the system operator to activate flexibility service from local responsive sources with the aim of addressing the regulation-voltage issue in the grid. Respectively, the system operator as the leader provides incentive control signals to ensure collaboration of the independent agents in voltage regulating procedure. Finally, the developed framework is applied on the 37-bus IEEE test network to investigate its application in mitigating the regulation-voltage issue in the active distribution systems with multi-agent formations.

INDEX TERMS Active distribution system, renewable energy, voltage issue, flexibility, multi-agent systems, DER, responsive sources.

I. INTRODUCTION

Active distribution systems (ADSs) are developed by the introduction of small-scale power generation units as well as storage units and responsive loads in power networks. In this regard, the installation of distributed energy resources (DERs) in ADSs has resulted in changing the conventional operating procedures in the grid [1]. In this context, renewable energy sources (RESs) would play a key role in supply the loads in ADSs. Respectively, installation of RESs, i.e. photovoltaic (PV) and wind power units, in ADSs is supported based on reducing the fossil fuel consumption and environmental aspects as well as decreasing the power loss in the grid. Nevertheless, the high-level penetration of RESs could cause operating issues in the system. In this regard, over-power generation by RESs could result in regulation-voltage issues in the ADS. Consequently, a new managing scheme should be established in order to enable the ADS operator (ADSO) to address the potential regulation-voltage issues in ADSs.

In recent years, several research works have focused on optimizing the scheduling of local sources in ADSs in order to address the regulation-voltage issue in the grid. Respectively, a hierarchical managing scheme is proposed in [2] in order to ensure the coordinated operational scheduling of storage units, which would finally facilitate...
regulation-voltage in ADSs with the high installation of PV units. In this context, independent aggregators optimize the scheduling of storage units in the lower level; while, the upper level aims to coordinate the operation of aggregators in order to ensure the regulated voltage in the grid. Moreover, authors in [3] have conducted a thorough review of the effects of the distributed generation units on the operation of the system from the protection and regulating voltage point of view. Furthermore, in [4], a chance-constrained centralized optimization formulation is proposed to address the overvoltage in ADSs with the high-level integration of PV units. In addition, Aryaneghad [5] has developed a scheme for managing and coordinating of scheduling of local sources to regulate the voltage as well as minimizing the power loss in ADSs, which indicates the application of storage units in improving the voltage magnitudes of the ADS. Moreover, a coordination framework is proposed in [6] in order to optimize the scheduling of storage units with the aim of regulating the voltage in ADSs with the high-level integration of PV units.

Based on the above discussions, ADSOs as entities responsible for the reliable operation of ADSs have to exploit the scheduling of local sources to address the regulation-voltage issue in systems with high-levels of RESs. In other words, the outcome of the day-ahead market in power grids may not be associated with the limitation of ADSs. In other words, the constraints of local grids are not taken into account in the day-ahead wholesale markets, which could result in the regulation-voltage issue in ADSs with high-level integration of RESs. As a result, ADSO would rely on the re-scheduling of local responsive sources in order to regulate the voltage in the system without causing RESs/demands curtailment. Nevertheless, the distributed formation of modern ADSs, which is developed as a result of privatization and restructuring would impede the direct access of the ADSO over the scheduling of the local sources. In other words, while the multi-agent formation of modern systems facilitates the installation of independently operated sources into the power grids; system operators could not directly change their scheduling to regulate the voltage in the ADS. In multi-agent systems, local sources would be operated by independent agents, which could provide system operators with the flexibility service to efficiently operate the ADS. Consequently, novel managing schemes should be developed to enable the ADSOs to activate flexibility service from the local responsive sources in order to regulate the voltage in the ADS. Respectively, system operators could provide incentive control signals for independent agents in order to exploit their power scheduling. In this context, authors in [7] have developed a scheme, in which the system operator provides incentives for energy storage systems to manage the variable power flows in the power grids. Furthermore, a case study for activation of residential flexibility in ADSs in exchange of a reward in order to manage the peak power in the system is investigated in [8].

As mentioned, ADSO would be able to employ a reward-based model in order to incentivize the involvement of independent agents in the regulating voltage procedure in the ADS, which would finally mitigate the potential RESs curtailment due to the regulation-voltage issue in systems with high-level integration of RESs. In this context, hierarchical formations based on the Stackelberg game could be employed to enable the ADSO to exploit the operating scheduling of independently operated responsive sources. Correspondingly, hierarchical modeling is taken into account in [9] to activate the demand response flexibility to address the variability of the wind power agent while participating in the power market model. Nevertheless, the offered model has not investigated the network modeling and overlooked the regulation-voltage issue in the ADS. Moreover, a review over the application of the Stackelberg game model as well as the cooperative and non-cooperative games for managing the integrated energy systems is conducted in [10]. Furthermore, authors in [11] have studied the application of the hierarchical Stackelberg game in modeling the incentive demand response in energy systems.

Taking into account the above discussions regarding the necessity of considering the re-scheduling of responsive sources in systems with the high-level integration of RESs to address the regulation-voltage issue, this paper aims to develop a hierarchical managing model to facilitate the involvement of the independent agents in the regulating voltage procedure in multi-agent ADSs with high-level penetration of RESs. In this regard, while the conventional manners for regulating the voltage in the ADS are not effective, the ADSO would offer rewards to the system agents in order to incentivize their collaboration in regulating the voltage in the grid. It is noteworthy that the traditional regulating voltage techniques may hardly adapt to the new operating condition of the system and could not regulate the voltage without exploiting the active power transactions of the agents. Respectively, ADSO as the leader strives to mitigate the regulation-voltage issue in the grid by exploiting the scheduling of independently operated responsive sources, which would finally minimize the probable RESs curtailment in the system. Furthermore, each agent as a follower aims to maximize its profit while providing operating service for the ADSO. Note that the ADSO, as the entity responsible for the operation of the grid, would prefer to address the regulation-voltage issue with the minimum reward payment. Based on the offered approach, while most of the previous research works have merely considered the operating scheduling of storage units in a central manner to address the regulation-voltage issue in the grid, the offered scheme in this paper strives to investigate the role of different types of responsive sources as well as considering the multi-agent formation of the system. In this regard, the information exchange between the ADSO and agents is limited to the reward signals and the changes in the accumulated power requests to cope with the multi-agent formation of the system.

In this paper, a reward-based managing scheme is developed in order to activate flexibility service from local responsive sources to address the regulation-voltage issue in the
grid. In this regard, modeling of the ADS with a multi-agent formation is illustrated in Section II.A. Moreover, the offered framework for mitigating the regulation-voltage issue in the grid by re-scheduling the local responsive sources in the ADS is explained in Section II.B. In this regard, the mathematical formulations of the optimizations employed by the independent agents of the system as well as the ADSO to respectively maximize/minimize their profit/cost are presented in Section II.C. Furthermore, the derived one-level optimization formulation for determining the optimal rewards as well as re-scheduling of agents is presented in Section II.D. Note that the iterative algorithm for mitigating the regulation-voltage issue in the grid considering the rebound effects of the energy-limited sources is presented in Section II.D. Finally, simulation results associated with employing the offered scheme for mitigating the regulation-voltage issue in the IEEE-37 bus test network are presented and discussed in Section III, followed by the conclusion in Section IV.

II. METHODOLOGY
A. MODELING OF MULTI-AGENT ADSs
Privatization in ADSs which is introduced to facilitate the installation of DERs has resulted in the development of multi-agent formations. In this formation, ADSO would not have direct access to the operating scheduling of each of the local sources to address the privacy concerns of the independent prosumers. Respectively, this paper conceives active ADSs with multi-agent formation as shown in Fig. 1, in order to facilitate the high-level integration of RESs and responsive sources into the grid. As a result, as presented in Fig. 1, without loss of generality, it is conceived that each agent of the system would merely operate a type of local sources (i.e. responsive loads, storage units, conventional distributed generation units, and RESs) to completely investigate the role of each responsive sources in regulating the voltage in the grid. In this context, R-Agent $i$, DG-Agent $i$, D-Agent $i$, and ESS-Agent $i$ present the agents responsible for scheduling of RESs, conventional distributed generation, responsive loads, and storage units in node $i$ of the network, respectively.

![FIGURE 1. The considered model for ADSs with multi-agent formation.](image)

B. HIERARCHICAL REWARD-BASED REGULATING VOLTAGE FRAMEWORK
In multi-agent ADSs, ADSO would act as the responsible entity for operating the grid in a reliable manner; while, each agent schedules their sources independently. As mentioned, conventional regulating voltage procedures may not adapt to the new operating condition in active ADSs with the high-level integration of RESs. Respectively, ADSO aims to acquire operating service from local responsive sources in order to regulate the voltage in the grid. ADSO should therefore exploit the scheduling of local responsive sources after clearing the day-ahead market to ensure that the system would not confront the regulation-voltage issue. Consequently, a reward-based mechanism is developed in this paper in order to enable the ADSO to incentivize the involvement of responsive sources in mitigating the regulation-voltage issue in the grid to ensure the reliable operation of the grid. As a result, a hierarchical formation based on the Stackelberg game is developed to determine the optimal re-scheduling of independent agents as well as their received rewards from the ADSO. In this context, ADSO has the leader role in the offered scheme, while agents as followers re-schedule their sources based upon the received rewards. Furthermore, the strong duality concept is taken into account in order to recast the bi-level operating formulation into a one-level optimization, which would determine the optimal outcomes of the model for regulating the voltage in the grid. In addition, considering the rebound effect in the re-scheduling of energy-limited responsive sources, an iterative algorithm is proposed to apply the one-level optimization formulation for addressing the regulation-voltage issue in the grid. Finally, it is noteworthy that the operating service provided by responsive sources would mitigate the over-voltage issue caused by the over-power generation of RESs in the system, which would facilitate the high-level integration of RESs in ADSs without compromising the reliability of the system. A simplified model of the interaction between entities in the system is presented in Fig. 2. In this regard, the information exchange between the ADSO and agents is limited to the reward signals and to the changes in the accumulated power requests, which copes with the multi-agent formation of the system.

C. MATHEMATICAL MODELING OF THE SCHEME
Based on the offered bi-level scheme for regulating the voltage in a multi-agent ADS, ADSO strives to induce re-scheduling of independent agents by offering rewards (i.e. $\rho^{Agent} \times \Delta P^{Agent}$) to them. In this respect, independent agents as followers in the developed model re-schedule their responsive sources with the aim of maximizing their profits while providing the ADSO with operating service for mitigating the regulation-voltage issue in the grid. In this regard, the following sub-sections illustrate the formulation from each entity’s perspective, as well as the one-level formulation to determine the optimal re-scheduling of the agents as well as the offered rewards by the ADSO. In this context, as the developed scheme conducts after clearing the day-ahead market, $\rho^{Agent, Pos}$ presents the reward offered by the ADSO to incentivize the respective agent to increase/decrease its demand/generation. Similarly, $\rho^{Agent, Neg}$ indicates the offered reward for
decreasing/increasing the power demand/generation by the respective agent. In other words, $\rho_{\text{agent,Pos}}$ presents the offered reward to compensate the increase in the power request of the respective agent, while, $\rho_{\text{agent,Neg}}$ models the offered reward to incentivize the decrease in the power request of the agent. Furthermore, the agents would be able to participate in the power market while conducting the offered scheme. In this regard, as the developed scheme would be conducted after clearing the day-ahead market to address the regulation-voltage issues raised by the market outcome, without loss of generality, it is conceived that the agents would be able to participate in the in-day market. In this regard, $\lambda_{\text{buy}}$ shows the price of the power purchase from the market, while $\lambda_{\text{sell}}$ models the price of selling power to the upper-level network. Note that the model could be conducted at any time interval to address the regulation-voltage issue, and therefore the power prices would be associated with the power market at the respective time interval.

1) RE-SCHEDULING OF RESPONSIVE LOADS

Responsive loads could provide the operating service to the ADSO in case of receiving the reward offers that compensate their loss of profit. In this regard, the formulation associated with the re-scheduling of responsive loads operating by the load agent at node $i$ is as follows:

$$
\text{Max } \psi_i^D = \sum_{t \in T} \left( \Delta P_{i,t}^{D,Pos} \rho_{l_{i,t},i}^{\rho_{D,Pos},\text{Pos}} + \Delta P_{i,t}^{D,Neg} \rho_{l_{i,t},i}^{\rho_{D,Neg},\text{Neg}} \right) \quad (1a)
$$

Subject to $0 \leq \Delta P_{i,t}^{D,Pos} \leq \Delta P_{i,t}^{\text{Max},D,Pos}$

$0 \leq \Delta P_{i,t}^{D,Neg} \leq \Delta P_{i,t}^{\text{Max},D,Neg}$

$$
\sum_i \left( \Delta P_{i,t}^{D,Pos} - \Delta P_{i,t}^{D,Neg} \right) = 0 \quad (1d)
$$

where, $\rho_{l_{i,t},i}^{\rho_{D,Pos},\text{Pos}}$, $\rho_{l_{i,t},i}^{\rho_{D,Neg},\text{Neg}}$, $\lambda_{\text{buy}}$, and $\lambda_{\text{sell}}$ present the rewards offered to the responsive load agent at bus $i$ and the price of energy exchange with the upper network at the time interval $t$, respectively. Moreover, $\Delta P_{i,t}^{D,Pos}$, $\Delta P_{i,t}^{D,Neg}$, $\Delta P_{i,t}^{\text{Max},D,Pos}$, and $\Delta P_{i,t}^{\text{Max},D,Neg}$, correspondingly, show the increase and decrease in the power consumption by load agent in node $i$ at time $t$ as well as their associated maximum boundaries. In the formulation, the objective function in (1a) strives to maximize the profits of the load agent, while, (1b)-(1c) enforce the operating constraints associated with the changes in the power consumption of responsive loads. Moreover, constraint (1D) ensures the energy requirement by the responsive loads would be supplied during the optimization period.

2) RE-SCHEDULING OF ENERGY STORAGE SYSTEMS

The optimization associated with agents, operating the energy storage systems (ESSs), in order to maximize their profits while providing the flexibility service to the grid for regulating the voltage is formulated as follows:

$$
\text{Max } \psi_i^{\text{ESS}} = \sum_{t \in T} \left( \left( \rho_{l_{i,t},i}^{\rho_{\text{ESS},Pos},\text{Pos}} \Delta P_{i,t}^{\text{ESS},Ch,Pos} + \rho_{l_{i,t},i}^{\rho_{\text{ESS},Neg},\text{Neg}} \Delta P_{i,t}^{\text{ESS},Ch,Neg} \right) 
+ \left( \rho_{l_{i,t},i}^{\rho_{\text{ESS},Neg},\text{Pos}} \Delta P_{i,t}^{\text{ESS},Dis,Pos} + \rho_{l_{i,t},i}^{\rho_{\text{ESS},Neg},\text{Neg}} \Delta P_{i,t}^{\text{ESS},Dis,Neg} \right) \right) \quad (2a)
$$

Subject to

$0 \leq \Delta P_{i,t}^{\text{ESS},Ch,Pos} \leq \Delta P_{i,t}^{\text{Max},\text{ESS},Ch,Pos}$

$0 \leq \Delta P_{i,t}^{\text{ESS},Ch,Neg} \leq \Delta P_{i,t}^{\text{Max},\text{ESS},Ch,Neg}$

$0 \leq \Delta P_{i,t}^{\text{ESS},Dis,Pos} \leq \Delta P_{i,t}^{\text{Max},\text{ESS},Dis,Pos}$

$0 \leq \Delta P_{i,t}^{\text{ESS},Dis,Neg} \leq \Delta P_{i,t}^{\text{Max},\text{ESS},Dis,Neg}$

$$
D_{E_{i,t}}, \text{Min} \leq D_{E_{i,t}} \leq D_{E_{i,t}}, \text{Max} \quad (2b)
$$

$$
D_{E_{i,t+1}} = D_{E_{i,t}} + \left( \frac{\eta_{\text{ESS},Ch}}{\eta_{\text{ESS},Dis}} \left( \Delta P_{i,t}^{\text{ESS},Ch,Pos} - \Delta P_{i,t}^{\text{ESS},Ch,Neg} \right) - \left( \Delta P_{i,t}^{\text{ESS},Dis,Pos} - \Delta P_{i,t}^{\text{ESS},Dis,Neg} \right) \right) \quad (2g)
$$

where, $\rho_{l_{i,t},i}^{\rho_{\text{ESS},Pos},\text{Pos}}$ and $\rho_{l_{i,t},i}^{\rho_{\text{ESS},Neg},\text{Neg}}$ represent the rewards offered by the ADSO to incentivize increasing/decreasing the power request by the ESS agent at node $i$, while re-scheduling of ESS units. Furthermore, $\Delta P_{i,t}^{\text{ESS},Ch,Pos}$, $\Delta P_{i,t}^{\text{ESS},Ch,Neg}$, $\Delta P_{i,t}^{\text{ESS},Dis,Pos}$, $\Delta P_{i,t}^{\text{ESS},Dis,Neg}$, and $\Delta P_{i,t}^{\text{Max},\text{ESS},Ch,Pos}$, $\Delta P_{i,t}^{\text{Max},\text{ESS},Ch,Neg}$, $\Delta P_{i,t}^{\text{Max},\text{ESS},Dis,Pos}$, and $\Delta P_{i,t}^{\text{Max},\text{ESS},Dis,Neg}$ show the increase and decrease in the power charging of the storage units as well as their respective maximum limitations. Moreover, the increase and decrease in power discharging of the storage units, as well as their maximum bounds, are represented by $\Delta P_{i,t}^{\text{ESS},Ch,Pos}$, $\Delta P_{i,t}^{\text{ESS},Dis,Pos}$, $\Delta P_{i,t}^{\text{ESS},Dis,Neg}$, and $\Delta P_{i,t}^{\text{Max},\text{ESS},Dis,Pos}$. 

FIGURE 2. The hierarchical distributed managing scheme for mitigating the regulation-voltage issue in the grid.
and $\Delta P_{i,t}^{Max,ESS,Dis,Neg}$. In addition, the stored energy of the ESS units and their operating bounds are presented by $DE_{i,t}^{ESS}$, $DE_{i,t}^{Max,ESS}$ and $DE_{i,t}^{Min,ESS}$, respectively. Note that in the developed formulation, objective (2a) strives to maximize the profits of the agent considering the rewards offered by the ADSO. Moreover, the limitations over the changes in the charging/discharging of the storage units are enforced by (2b) – (2e). Finally, the stored energy in the storage units, as well as its bounds, are shown in (2f) – (2g).

3) RE-SCHEDULING OF CONVENTIONAL DISTRIBUTED GENERATION UNITS

Conventional distributed generation (CDG) units could benefit the grid by providing operating services for system operators to address operating issues in the grid. In this regard, the formulation employed by agents, responsible for the operation of the conventional distributed generation units, based on the received reward offers from the ADSO is formulated as follows:

$$\text{Max } \psi_i^{CDG} = \sum_{t \in T} \left( \left( \frac{\phi_{l,i}^{CDG,Pos} - \theta_{l,i}^{buy}}{\phi_{l,i}^{CDG,Pos}} \right) \Delta P_{i,t}^{CDG,Neg} + \left( \frac{\phi_{l,i}^{CDG,Neg} + \theta_{l,i}^{sell}}{\phi_{l,i}^{CDG,Neg}} \right) \Delta P_{i,t}^{CDG,Pos} \right) \Delta P_{i,t}^{CDG} - \Delta P_{i,t}^{CDG,Pos} \right) + \Delta P_{i,t}^{CDG,Neg} \right) C_{l,i}^{CDG}$$

Subject to $0 \leq \Delta P_{i,t}^{CDG,Pos} \leq \Delta P_{i,t}^{Max,CDG,Pos}$

$0 \leq \Delta P_{i,t}^{CDG,Neg} \leq \Delta P_{i,t}^{Max,CDG,Neg}$

where, $\phi_{l,i}^{CDG,Pos}$, $\phi_{l,i}^{CDG,Neg}$, and $C_{l,i}^{CDG}$, respectively, present the offered rewards to the agent as well as the operating costs of the CDG units. Furthermore, $\Delta P_{i,t}^{CDG,Pos}$, $\Delta P_{i,t}^{CDG,Neg}$, $\Delta P_{i,t}^{Max,CDG,Pos}$, and $\Delta P_{i,t}^{Max,CDG,Neg}$ show the increase and decrease in the power production by the CDG units as well as their respective maximum limitations. In the offered formulation, the objective function in (3a) strives to maximize the profits of the agent at node $i$, while the constraints over the changes in the power production by the conventional-DG units are represented in (3b) – (3c).

4) ADSO FORMULATION MODELLING

As discussed in previous sections, it is conceived that the conventional procedures such as reactive power injections and the tap changers could not completely mitigate the regulation-voltage issue in the ADSs with the high-level penetration of RESs. As a result, ADSO would rely on exploiting the scheduling of local responsive for improving the voltage magnitudes in the ADS. Respectively, the formulation conducted by the ADSO considering the convex-form of DistFlow model [12]–[14] to prevent the probable curtailment of RESs in the system due to the high-voltage issue is shown in (4). It is noteworthy that the ADSO would provide the reward to incentivize re-scheduling of responsive sources for regulating the voltage in the grid; which would finally minimize the RESs curtailment and power losses.

Min $C_{\text{Voltage\_Regulation}}$

$$= \sum_{i \in T} \sum_{t \in T} \left( \left( \frac{\phi_{l,i}^{D,Pos}}{\phi_{l,i}^{D,Pos}} \right) \Delta P_{i,t}^{D,Pos} + \left( \frac{\phi_{l,i}^{D,Neg}}{\phi_{l,i}^{D,Neg}} \right) \Delta P_{i,t}^{D,Neg} + \left( \frac{\phi_{l,i}^{ESS,Pos}}{\phi_{l,i}^{ESS,Pos}} \right) \Delta P_{i,t}^{ESS,Pos} + \left( \frac{\phi_{l,i}^{ESS,Neg}}{\phi_{l,i}^{ESS,Neg}} \right) \Delta P_{i,t}^{ESS,Neg} + \left( \frac{\phi_{l,i}^{CDG,Pos}}{\phi_{l,i}^{CDG,Pos}} \right) \Delta P_{i,t}^{CDG,Pos} + \left( \frac{\phi_{l,i}^{CDG,Neg}}{\phi_{l,i}^{CDG,Neg}} \right) \Delta P_{i,t}^{CDG,Neg} + \left( \frac{\phi_{l,i}^{RES,curtail}}{\phi_{l,i}^{RES,curtail}} \right) \Delta P_{i,t}^{RES,curtail} \right) + C_{\text{Network\_Dloss}}$$

Subject to $\Delta P_{i,t}^{CDG} = \Delta P_{i,t}^{D,Pos} - \Delta P_{i,t}^{D,Neg} + \Delta P_{i,t}^{ESS,Pos} + \Delta P_{i,t}^{ESS,Neg} + \Delta P_{i,t}^{CDG,Pos} + \Delta P_{i,t}^{CDG,Neg} - \Delta P_{i,t}^{RES}$

$V_{i,t}^{Min} \leq V_{i,t} \leq V_{i,t}^{Max}$

$0 \leq \Delta P_{i,t}^{RES,curtail} \leq \Delta P_{i,t}^{Max,RES,curtail}$

where, $\phi_{l,i}^{RES,curtail}$, and $\Delta P_{i,t}$, respectively, show the cost associated with the curtailment of RESs as well as the total changes in the power injection in node $i$ at time $t$. Furthermore, $\Delta P_{i,t}^{RES,curtail}$ and $\Delta P_{i,t}^{Max,RES,curtail}$ represent the changes in the power generation by RESs in node $i$ at time $t$ as well as its maximum limitations. Moreover, $C_{\text{Voltage\_Regulation}}$, and $C_{\text{Network\_Dloss}}$ present the cost of alleviating the regulation-voltage issue in the network by exploiting the scheduling of local sources as well as the cost associated with the changes in the network power losses. In the developed optimization formulation, the objective function in (4a) strives to minimize the cost associated with the re-scheduling of local sources for regulating the voltage in the grid. In this respect, the cost associated with the offered rewards to agents and the curtailment of RESs, as well as the cost associated with the changes in the power losses are modeled in the objective function. Moreover, the change in the power injection of each node of the system at each time interval is presented in (4b), while, the operating modeling of the grid is presented in (4c). Finally, the limitations over the voltage magnitudes in the grid are enforced by (4d), whereas, the bounds associated with the curtailment of RESs are indicated by (4e).

In the offered formulation for regulating the voltage in a multi-agent ADS, the ADSO would offer rewards to the agents in case of their involvement in regulating the voltage process. In this respect, the cost of rewards as well as the cost associated with the changes in the network power losses due to the re-scheduling of agents are taken into account.
by ADSO; while each agent considers the price of power exchange with the upper-network as well as the received reward offers from the ADSO. In this regard, agents are responsible for the cost associated with the rescheduling of their sources. Respectively, the developed formulation complies with the multi-agent formation of future ADSs. In this regard, to solve the model with the efficient computation, the Strong duality theory is taken into account in the following section to recast the bi-level model into a one-level optimization issue [10, 15]. In other words, the developed one-level formulation would converge to the optimal solution of the regulation-voltage issue by determining the optimal reward signals as well as the re-scheduling of local sources in the system.

D. DEVELOPMENT OF THE ONE-LEVEL FORMULATION

As mentioned, for efficient computation, the developed bi-level model is recast into a one-level formulation to determine the optimum rewards as well as the re-scheduling of the system agents. In this regard, the constraints of the lower formulations (i.e. mathematical formulations of the agents), as well as the constraints of their dual formulations, are added to the optimization of the ADSO to ensure that the developed one-level optimization would converge to the optimal outcome of the bi-level issue. Respectively, the obtained one-level formulation could be modeled as follows:

\[
\begin{align*}
\text{Min } & C_{\text{Voltage}\_\text{Regulation}} \\
\text{subject to } & (1b)-(1d), (2b)-(2g), (3b)-(3c), \text{ constraints of (4) and (5)} \\
& \sum_{t \in T} \left( \Lambda_{D, t, \text{Pos}} + \Delta \Lambda_{D, t, \text{Max}, \text{Pos}} \right) = \psi_{\text{D}} 
\end{align*}
\]

\[
\begin{align*}
\Lambda_{D, t, \text{Pos}} + \Lambda_{D, t, \text{ED}} & \geq \rho_{t, t} - \lambda_{t} \text{ buy} \\
\Lambda_{D, t, \text{Neg}} - \Lambda_{D, t, \text{ED}} & \geq \rho_{t, t} + \lambda_{t} \text{ sell} \\
\Lambda_{i, t, \text{Pos}} & \times \Delta \Lambda_{i, t, \text{Max}, \text{Pos}} \geq \psi_{i} \\
\Lambda_{i, t, \text{Neg}} & \times \Delta \Lambda_{i, t, \text{Max}, \text{Neg}} \geq -\psi_{i} \\
\Lambda_{i, t, \text{Pos}} \times \Delta \Lambda_{i, t, \text{Max}, \text{Pos}} & \geq \rho_{t, t} - \lambda_{t} \text{ buy} \\
\Lambda_{i, t, \text{Neg}} \times \Delta \Lambda_{i, t, \text{Max}, \text{Neg}} & \geq -\rho_{t, t} + \lambda_{t} \text{ sell} \\
\Lambda_{\text{ESS}, t, \text{Ch}} \times q - \eta_{i} \Lambda_{\text{ESS}, t, \text{Dis}} & \leq \rho_{t, t} \text{ buy} \\
\Lambda_{\text{ESS}, t, \text{Ch}} & \geq -\rho_{t, t} + \lambda_{t} \text{ sell} \\
\Lambda_{\text{ESS}, t, \text{Ch}} - \Lambda_{\text{ESS}, t, \text{Neg}} & \geq \rho_{t, t} \text{ buy} \\
\Lambda_{\text{ESS}, t, \text{dis}} & \geq -\rho_{t, t} + \lambda_{t} \text{ sell} \\
\sum_{t \in T} \left( \Lambda_{i, t, \text{Pos}} \times \Delta \Lambda_{i, t, \text{Max}, \text{Pos}} \right) & \geq \psi_{i} 
\end{align*}
\]

In the developed one-level optimization issue, constraints (5b) – (5d), (5e) – (5j), and (5k) – (5m), correspondingly, represent the dual models of the optimizations associated with the agents operating load, energy storage systems, and conventional distributed generation units. Respectively, \( \Lambda_{D, t, \text{Pos}}, \Lambda_{D, t, \text{Neg}}, \Lambda_{D, t, \text{ED}}, \Lambda_{i, t, \text{Pos}}, \Lambda_{i, t, \text{Neg}}, \Lambda_{i, t, \text{ED}}, \Lambda_{i, t, \text{Ch}}, \Lambda_{i, t, \text{Neg}}, \Lambda_{\text{ESS}, t, \text{Ch}}, \Lambda_{\text{ESS}, t, \text{Dis}}, \Lambda_{\text{Min}, \text{ESS}}, \Lambda_{\text{Max}, \text{ESS}} \) indicate the Lagrangian multiplier variables of the constraints (1b)-(1d), (2b)-(2g), and (3b)-(3c). Furthermore, in order to ensure that the charging and discharging of the storage units would not simultaneously occur in the system, constraints (5n)-(5p) are taken into account in the developed optimization formulations. In this regard, \( \alpha_{i, t, \text{Ch}} \) and \( \alpha_{i, t, \text{Dis}} \) show the binary variables, which present the active operating mode of the storage units at the respective time step. In this context, \( \rho_{t, t}^{\text{DA}, \text{ESS, Ch}}, \rho_{t, t}^{\text{DA}, \text{ESS, Dis}}, \rho_{t, t}^{\text{Max}, \text{ESS}, \text{Ch}}, \rho_{t, t}^{\text{Max}, \text{ESS}, \text{Dis}} \) show the scheduled day-ahead charging and discharging of the storage units, as well as the maximum limitations of the charging and discharging of the units.

In the offered reward-based scheme for the voltage profile improvement of the grid, ADSO would offer rewards to the agents at time intervals that the grid confronts with the regulation-voltage issue in order to incentivize their involvement in providing the flexibility service for regulating the voltage of the grid. Nevertheless, due to the rebound effect, re-scheduling of energy-limited sources at time intervals that the grid confronts with the regulation-voltage issue may cause the violation of the voltage limitations at other time intervals. As a result, an iterative algorithm is developed in this paper to ensure the rebound effects associated with the re-scheduling of energy-limited sources would not cause regulation-voltage issues at other time intervals in the grid. In this regard, as shown in Fig. 3, the time intervals that the grid confronts with the regulation-voltage issue are included in the one-level formulation in an iterative manner to ensure the optimum results would not violate the grid’s regulation-voltage at other time intervals. Respectively, the offered iterative algorithm would continue until the step that the outcome of the
optimization copes with the regulation-voltage limitations at all time intervals.

It is noteworthy that the information exchange between the agents and the ADSO in the offered model is limited to the accumulated possible changes in the power injection of each agent as well as the offered reward signals. In this respect, the developed algorithm for improving the voltage profile of the grid in multi-agent ADSs copes with the distributed formation of the system. Finally, the non-linear terms (i.e. $\rho^\text{Agent} \times \Delta P^\text{Agent}$) in the offered one-level optimization formulation are linearized utilizing the SOS2 algorithm shown below:

$$\tau^\text{Agent} = \rho^\text{Agent} \times \Delta P^\text{Agent} \quad (6a)$$

$$\tau^\text{Agent} \geq \rho^\text{Agent, max} \times \Delta P^\text{Agent} + \rho^\text{Agent} \times \Delta P^\text{Agent, max} - \rho^\text{Agent, max} \times \Delta P^\text{Agent, max} \quad (6b)$$

$$\tau^\text{Agent} \geq 0 \quad (6c)$$

$$\tau^\text{Agent} \leq \rho^\text{Agent, max} \times \Delta P^\text{Agent} \quad (6d)$$

$$\tau^\text{Agent} \leq 0 \quad (6e)$$

In this regard, by including equations (6a)-(6e) and replacing $\rho^\text{Agent} \times \Delta P^\text{Agent}$ by $\tau^\text{Agent}$ in the developed one-level formulation, the linearized model would be obtained.

### III. CASE STUDY

The offered algorithm for regulating the voltage in the grid considering the re-scheduling of the responsive sources is implemented on the IEEE-37 bus test network [16], [17], which is shown in Fig. 4, to investigate its application for improving the voltage profile of the systems with the high-level integration of RESs. Note that the system is considered to be structured as a multi-agent network represented in Fig. 1. As discussed, in the conceived multi-agent system, each agent would optimize its scheduling, while ADSO offers rewards to incentivize their involvement in mitigating the regulation-voltage issue in the grid. As a result, the agents operating the conventional distributed generation units, loads, as well as storage units would re-schedule their sources to maximize their profits. Note that the operating characteristics of the test system as well as the local sources are presented in [18].

As mentioned, it is conceived that as the conventional manners have failed to address the regulation-voltage issue in the grid; therefore, ADSO has to exploit the operating scheduling of responsive sources to prevent probable curtailment of RESs. In other words, the grid would be confronted with the over-voltage issue due to the high penetration of RESs in the multi-agent system. Respectively, the voltage magnitude of the grid at nodes 15, 25, 30, and 35 before and after employing the offered algorithm for improving the voltage magnitudes is presented in Fig. 5. In this regard, the offered algorithm addresses the high-voltage issue in the grid at hours 9-16. Moreover, the voltage profile of the grid before and after the implementation of the offered scheme at hour 12 is shown in Fig. 6. Based on the obtained results, the developed approach enables the ADSO to incentivize the involvement of local responsive sources to address the high voltage issue in the grid, which is occurred due to the high-level integration of RESs in modern ADSs. Note that, based on the offered algorithm in Fig. 3, the algorithm is conducted for two iterations to mitigate the regulation-voltage issue in the grid. In other words, due to the rebound effects of energy-limited sources, the obtained results in the first step violate the regulation-voltage in nodes 34, 35, and 36 at hour 16. Nevertheless, the results of the developed one-level optimization in the second iteration considering the high-voltage issue at hours 9 – 16 address the voltage constraints of the grid at all time intervals. Based on the obtained results, the changes in the power scheduling of agents operating the responsive loads, conventional distributed generation units, and storage units are shown in Figs. 7 - 10. In this context, the power request of storage units and loads are increased at
hours 9 – 16 to address the high power production by RESs; while, their power request is increased at other time intervals in order to ensure their energy requests would be addressed. Furthermore, to decrease the power injection at each node of the grid, the power generation by conventional distributed generation units is decreased at hours 9 – 16 that the ADSO offered rewards to incentivize their involvement of independent agents in mitigating the regulation-voltage issue in the grid. In addition, the rewards received by the agents operating the responsive loads, storage units, and conventional distributed generation units are represented in Figs. 11 – 13. Respectively, the rewards offered by the ADSO would incentivize the increase in power requests of storage units and responsive loads in the system to alleviate the regulation-voltage issue. In this regard, as shown in Figs. 5 and 6, the regulation-voltage issue is more severe at nodes far from the common coupling point of the distribution and transmission.
systems (i.e. node 0), therefore, the over power production by RESs is tried to be compensated locally by the responsive sources in these nodes to address the over-voltage issue in the network. Furthermore, the rewards associated with the agents operating the conventional distributed generation units incentivize their collaboration in addressing the regulation-voltage issue in the grid by decreasing their power generation. Finally, the proportional increase in the overall offered rewards to system agents compared with the current condition, in the case of increasing the installed capacity of RESs in the system is presented in Fig. 14. Based on the obtained results, the offered algorithm for activation of local flexibility service to address the regulation-voltage issue in the grid would facilitate the high-level integration of RESs. In other words, the offered model enables the implementation of multi-agent formations with the high-level installation of RESs in ADSs without compromising the reliability of the grid. This approach would finally facilitate efficient managing of flexibility sources, which plays a key role in facilitating the development of smart energy systems with high-level penetration of RESs [19].

IV. CONCLUSION

In this paper, a hierarchical model is developed in order to enable the system operators of the ADS to address the regulation-voltage issue in the grid. Note that the conventional manners for regulating the voltage in the grid may not be able to address the regulation-voltage issue in systems with the high-level penetration of RESs. Respectively, ADSO should exploit the scheduling of local responsive sources to efficiently mitigate the regulation-voltage issues without curtailment of RESs. In this regard, the offered framework enables the ADSO to incentivize the involvement of local responsive sources in mitigating the regulation-voltage issue in the grid. Consequently, ADSO, as the leader, offers rewards to system agents to compensate for their involvement in providing operating services for regulating the voltage in the grid. Furthermore, the preliminary hierarchical model is re-cast into a one-level formulation, which is implemented in the system based on an iterative algorithm to determine the optimal re-scheduling of the power requests by each agent as well as the offered rewards by the ADSO.

The developed algorithm is applied on the IEEE-37 bus test network in order to study its effectiveness in the activation of flexibility service from local responsive sources to address the regulation-voltage issue in the grid. Finally, the obtained results show the application of the offered scheme for incentivizing the involvement of local responsive sources for mitigating the regulation-voltage issue in the grid; which, without compromising the reliability of the system, decreases the probable curtailment of RESs for improving the voltage profile of the grid.

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