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An Effective Approach for Locational Marginal Price Calculation at Distribution Level

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***Abstract*—This paper develops an effective approach for the locational marginal price calculation for local generations in an active distribution network containing different types of distributed generators (DGs). The proposed approach is based on encouraging private units to reduce power loss and greenhouse gas (GHG) emissions. To this end, firstly, the distribution system operator (DSO) surplus profit, obtained by the reduction of power loss and GHG gas emission due to the operation of private units in the network, is considered as a financial source for encouraging private units. Then, according to the contribution of each private DG, the locational marginal price is calculated. The proposed approach is an effective and incentive-based approach for DSO to retain control over private units to reduce power loss and GHG emissions. The simulation results on a modified 118-bus standard distribution test system demonstrate the efficiency of the proposed approach compared to the previous approaches.**

***Index Terms*— Locational marginal price, Power loss and GHG emission reduction, Iterative approach.**

Indices

j	Fuel-Based DG index, $j \in \boldsymbol{N}_{DG}$
l	Branch index, $l \in \Omega_{brch}$
n	Combined solar PV panel and energy storage system, $n \in \boldsymbol{N}_{PVES}$
t	Hourly scheduling intervals, $t \in \{1, 2, \dots, 24\}$
itr	Iteration index

Vectors/Sets

$\boldsymbol{b}^t$	Set of binary variables representing the status of availability or unavailability of lines
Ω_{brch}	Set of distribution network branches

Coefficients

a_j, b_j, c_j	Cost coefficients of the j^{th} fuel-based DG
em_{DG}^{j}	Emission coefficients of the j^{th} fuel-based DG
em_{ss}	Emission coefficients of the upstream grid
$\rho_{ch/dis}^{n}$	Charge/Discharge efficiency of the n^{th} energy storage

Parameters

$\mathcal{B}_{DSO}^{Conv/new}$	DSO profit for conventional/modern network
$\mathcal{B}_{DG}^{j}$	Profit of the j^{th} fuel-based DG
$\mathcal{B}_{PVES}^{n}$	Profit of the n^{th} PVES unit
BS_n^t	Charging/Discharging status of the n^{th} energy storage unit at t^{th} hour (i.e. $BS_n^t = 1$ is charging, and BS_n^t=0 is discharging)
BC_n^t	Auxiliary binary variable of the n^{th} energy storage unit at t^{th} hour
E_n^t	State of charge for n^{th} energy storage at t^{th} hour
$E_n^{(.)}$	Maximum (Minimum) state of charge for the n^{th} energy storage, $(.) = max, min$
$Em_{Conv/new}^{t}$	Emission of the conventional/modern system at t^{th} hour
$I_{l,Conv/new}^{t}$	Current flow of the l^{th} line in conventional/modern distribution network at t^{th} hour
$P_{PVES}^{n,t}$	Active power of the n^{th} PVES unit at t^{th} hour
$P_{PV}^{n,t}$	Active power of the n^{th} solar PV panel at t^{th} hour
$P_{Ch}^{n,t} \in \boldsymbol{P}_{Ch}^{n}$	Charge power of the n^{th} ES at t^{th} hour
$P_{Dis}^{n,t} \in \boldsymbol{P}_{Dis}^{n}$	Discharge power of the n^{th} ES at t^{th} hour
$P_{(.),n}^{max}$	Maximum charge/discharge active power of the n^{th} energy storage $(.)$= ch, dis
$P_{DG}^{j,(.)}$	Maximum (Minimum) capacity of the j^{th} fuel-based DG, $(.) = max, min$
P_{Ld}^{t}	Load demand at t^{th} hour ($P_{Ld}^t = \sum_{i \in \boldsymbol{N}_{bus}} P_{D,i}^t$)
$Ploss_{Conv/new}^{t}$	Power loss of conventional/modern system at t^{th} hour
$P_{DG}^{j,t}$	Active power of the j^{th} fuel-based DG at t^{th} hour
$(P_{ss}^{t})_{Conv/new}$	Active power from the substation for conventional/modern system at t^{th} hour
$Q_{PVES,n}^{(.)}$	Maximum (Minimum) boundary for reactive power of the n^{th} PVES inverter, $(.) = max, min$
$Q_{DG}^{j,t}$	Reactive power of the j^{th} fuel-based DG at t^{th} hour
$Q_{PVES}^{n,t}$	Reactive power of the n^{th} PVES unit at t^{th} hour
$RU^j (RL^j)$	Up (down) ramp rate limit of the j^{th} fuel-based DG
S_{DG}^{j}	Apparent power capacity of the j^{th} fuel-based DG
$\Delta\mathcal{B}_{DSO}$	Surplus profit of the DSO from the operation of the private units
$\Delta\mathcal{B}_{DSO}^{max}$	Maximum surplus profit of the DSO
α^{itr}	Accelerator/decelerator factor for controlling the DSO surplus profit
$\mathrm{N}_{ES,n}$	Maximum permitted number of switching back and forth between charging and discharging status of the n^{th} PVES unit
λ_D^t	Load demand price at t^{th} hour
λ_{ss}^t	Energy price at reference bus at t^{th} hour
λ_{Em}	Emission price for the substation
$\pi_{DG}^{j,t}$	Active power price for j^{th} fuel-based DG at t^{th} hour
$\pi_{PVES}^{n,t}$	Active power price for the n^{th} PVES unit at t^{th} hour

$\Lambda_{DG}^{j,t}$ Reactive power price for j^{th} fuel-based DG at t^{th} hour

$\Lambda_{PVES}^{n,t}$ Reactive power price for the n^{th} PVES unit at t^{th} hour

I. Introduction

The energy market at the distribution level develops quickly due to the increasing penetration of private generation units with different types of the distributed generator such as renewable energy resources. To provide a fair competition environment in the distribution-level energy market for all players, a distribution system operator (DSO) plays a crucial role in managing the market and improving the customers' social welfare in terms of reliability and service quality [1]. Among all the DSO strategies in managing the distribution electricity market, incentive-based strategies can effectively help the DSO engage private generation units and handle the relevant technical constraints [2]. Therefore, this paper targets a new iterative approach to calculate the locational marginal price (LMP) at the distribution level to maximize the engagement of private units in power loss and greenhouse gas (GHG) emissions.

Typically, a DSO can minimize power loss and GHG emission through two routes. The first route is to operate DSO-owned properties such as DGs directly. Along this route, there are many studies in maximizing the DSO profit using optimal dispatch of DGs and optimal charging and discharging patterns of energy storages (ESs) [3]. The second route is to indirectly operate private generation units by engaging private owners through incentive-based approaches. This second route provides the DSO surplus profit, and, in a fair competition, it should be minimized [2]. Therefore, this second route is an appropriate financial source for executing strategies to engage private units for better system performance [2, 4, 5].

Incentive-based strategies have appeared in the form of nodal price to comply with a specific objective function such as power loss, GHG emission reduction, or congestion management. For example, the proportional nucleolus theory-based iterative method was proposed in [6] for calculating LMP of DGs in distribution networks, with the aim of power loss reduction. A game theory-based iterative method is implemented in [7] to calculate the LMP at buses where DGs are allocated for emission and loss reduction. On the same track, authors in [8] use game theory to minimize the power losses of distribution systems by means of simultaneous performing reconfiguration and LMPs at buses in which DGs are installed. The contributions of these studies are valuable, and they have used the DSO's surplus profit as the financial source of incentive in the nodal price calculation. However, renewable energy resources as a key part of modern distribution networks have not been taken into account in these studies. Moreover, the technical constraints such as ramp-rate for the fuel-based units are not considered.

The aforementioned issues in the previous studies have been tackled in some studies in order to alleviate the possible congestion in distribution networks. For example, in [9], the DSO implements an LMP strategy for electric vehicles (EVs) to solve the distribution network congestion problem, and the corresponding LMP strategy is calculated with the help of mixed-integer programming. Similarly, for decreasing congestion in branches, a bi-level scheduling solution is offered as a distributional locational marginal pricing (DLMP) driven by EV aggregators. In greater detail, the upper level tries to alleviate the EV aggregator cost, while the lower level intends to maximize the social welfare of DSO considering the network restrictions [10]. Furthermore, Authors in [11] presents a heat-and-electricity-combined market framework for the nodal price calculation in distribution systems. These studies have offered valuable approaches, however, there is no control over the DSO surplus profit. Moreover, the fuel-based DGs as a key part of the distribution network in emergency cases have been neglected.

To solve these issues, this paper intends to present an effective approach for the locational marginal price calculation to maximize the engagement of private units in power loss and GHG emission reduction. In the introduced incentive-based LMP calculation, the DSO surplus profit from power loss and GHG emission reduction due to the operation of private units in the network is considered as the financial source to encourage private units. A significant reduction in power loss and GHG emission is achieved by transferring the surplus profit from the DSO to the private generation units using the LMP scheme. Overall, the main contributions of this paper are summarized as follows.

- Increasing the ability of DSO in the controllability of private units.
- Applicability of the proposed LMP calculation for distribution networks containing different types of private DGs.
- Considering the contribution of each private unit in power loss and GHG emission reduction for the LMP calculation.

The remainder of this paper is organized as follows. Section II presents the proposed mathematical formulation. Numerical studies are discussed in Section III, and some conclusions are drawn in Section IV.

II. Methodology

Before providing the mathematical model of the proposed problem, a list of assumptions related to the system description and structure, as well as the ownership of the facilities, are clarified as follows.

- The distribution network is integrated with private units, such as conventional fuel-based DGs, PV, and ES (PVES) units.
- All solar PV units are integrated with an ES unit to form a combined PV and ES (PVES) system, and the PV and ES belong to the same private owner. Consequently, for a PVES system, PV and ES share the same energy price.

A. Conventional distribution network

In conventional distribution networks without private units, the DSO profit (1a)-(1c) is obtained from finding the difference between the income from selling energy to the customers and expenditure for purchasing energy from upstream grids and paying emission charges.

$$\mathcal{B}_{DSO}^{Conv}=\sum_{t=1}^{24}\left(\lambda_D^t P_{Ld}^t-\lambda_{Em}Em_{Conv}^t-\lambda_{ss}^t(P_{Ld}^t+Ploss_{Conv}^t)\right) \quad (1a)$$

$$Em_{Conv}^t=em_{ss}(P_{ss}^t)_{Conv} \quad ,\forall t \quad (1b)$$

$$Ploss_{Conv}^t=\sum_{l\in\Omega_{brch}}R_l\left(I_{l,Conv}^t\right)^2 \quad ,\forall t \quad (1c)$$

B. Distribution network integrated with private units

Due to the presence of the DGs and in particular renewable energy resources, the operation of the distribution network has changed considerably. In modern distribution networks, the DSO purchases energy not only from the upstream grid, but also from private owners of DGs. Therefore, the updated form of DSO profit considering the energy transaction with private units is expressed in (2), in which $Ploss_{new}^{t}$, Em_{new}^{t}, and $(P_{ss}^{t})_{new}$ are the amount of power loss, GHG emission and the amount of power purchased from the upstream grid, respectively, when the network is operated in the presence of private units.

$$B_{DSO}^{new} = \sum_{t=1}^{24}\left(\begin{array}{c} \lambda_D^t P_{Ld}^t - \lambda_{ss}^t(P_{Ld}^t + Ploss_{new}^t) - \lambda_{Em} Em_{new}^t - \\ \sum_{j\in \boldsymbol{N}_{DG}} \left(\pi_{DG}^{j,t} - \lambda_{ss}^t\right) P_{DG}^{j,t} - \sum_{j\in \boldsymbol{N}_{DG}} \Lambda_{DG}^{j,t} Q_{DG}^{j,t} - \\ \sum_{n\in \boldsymbol{N}_{PVES}} \left(\pi_{PVES}^{n,t} - \lambda_{ss}^t\right) P_{PVES}^{n,t} - \sum_{n\in \boldsymbol{N}_{PVES}} \Lambda_{PVES}^{n,t} Q_{PVES}^{n,t} \end{array}\right) \tag{2a}$$

$$Em_{new}^t = em_{ss}(P_{ss}^t)_{new} + \sum_{j\in \boldsymbol{N}_{DG}} em_{DG}^j P_{DG}^{j,t} \qquad ,\forall t \tag{2b}$$

$$Ploss_{New}^t = \sum_{l\in\Omega_{brch}} R_l \left(I_{l,new}^t\right)^2 \qquad ,\forall t \tag{2c}$$

By comparing (1a) and (2a), it is obvious that there is a surplus profit for the DSO from power loss and emission reduction due to the operation of private units in the network.

In a fair competition environment, the DSO surplus profit from power loss and GHG emission reduction due to the operation of private units should be minimized [2]. In this regard, the DSO uses this surplus profit as a financial source to consider an incentive-based LMP for the owner of private units. Therefore, it can be an appropriate approach, in which the DSO can retain its control over the private units to gain the reduction of power loss and GHG emission in the distribution network. Toward this end, the DSO surplus profit is reformulated as (3).

$$\Delta\mathcal{B}_{DSO} = \mathcal{B}_{DSO}^{Conv} - \mathcal{B}_{DSO}^{new} = \sum_{t=1}^{24}\left(\begin{array}{c} \lambda_{ss}^t \Delta Ploss^t + \lambda_{Em}\Delta Em^t - \sum_{j\in \boldsymbol{N}_{DG}} \left(\pi_{DG}^{j,t} - \lambda_{ss}^t\right) P_{DG}^{j,t} \\ - \sum_{j\in \boldsymbol{N}_{DG}} \Lambda_{DG}^{j,t} Q_{DG}^{j,t} - \sum_{n\in \boldsymbol{N}_{PVES}} \left(\pi_{PVES}^{n,t} - \lambda_{ss}^t\right) P_{PVES}^{n,t} \\ - \sum_{n\in \boldsymbol{N}_{PVES}} \Lambda_{PVES}^{n,t} Q_{PVES}^{n,t} \end{array}\right) \tag{3a}$$

$$\Delta Ploss^t = Ploss_{Conv}^t - Ploss_{new}^t \qquad ,\forall t \tag{3c}$$

$$\Delta Em^t = Em_{Conv}^t - Em_{new}^t \qquad ,\forall t \tag{3d}$$

In the following, an iterative approach is introduced to calculate the LMP for active power ($\pi_{DG}^{j,t}$, $\pi_{PVES}^{n,t}$) and reactive power ($\Lambda_{DG}^{j,t}$, $\Lambda_{PVES}^{n,t}$), in which we reach the minimum value for the DSO surplus profit. In addition, the contribution of each DG in power loss and GHG emission reduction is also considered.

C. Locational marginal price calculation

Before introducing the iterative approach for LMP calculation, first, it needs to investigate the operation problem from the perspective of DG owners. Indeed, the goal of DG owners is to maximize their profits under given energy prices.

- *DG owners perspective*

The objective function for the optimal response from fuel-based DG owners is formulated in the following;

$$\mathcal{B}_{DG}^{j}\left(\pi_{DG}^{j}, \Lambda_{DG}^{j}\right) = \max_{\left(\boldsymbol{P}_{DG}^{j}, \boldsymbol{Q}_{DG}^{j}\right)} \left[\sum_{t=1}^{24}\left(\pi_{DG}^{j,t} P_{DG}^{j,t} + \Lambda_{DG}^{j,t} Q_{DG}^{j,t} - \left(a_j (P_{DG}^{j,t})^2 + b_j P_{DG}^{j,t} + c_j\right)\right)\right] \qquad ,\forall j \tag{4a}$$

$$s.t. \quad P_{DG}^{j,min} \le P_{DG}^{j,t} \le P_{DG}^{j,max} \qquad ,\forall\, t,j \tag{4b}$$

$$\left(P_{DG}^{j,t}\right)^2 + \left(Q_{DG}^{j,t}\right)^2 \le \left(S_{DG}^{j}\right)^2 \qquad ,\forall\, t,j \tag{4c}$$

$$RL^j \le P_{DG}^{j,t} - P_{DG}^{j,t-1} \le RU^j \qquad ,\forall\, t,j \tag{4d}$$

Eq. (4) represents the profit for the fuel-based DG units (4a) and its corresponding technical constraints, including the maximum and minimum capacity (4b)-(4c), and up/down ramp rate (4d).

In the PVES case, as the PV panels are not controllable, only ES units are considered in the owner's profit maximization process. Thus, the optimal charge and discharge pattern should be obtained for the 24-hour period by maximizing the owner's profit through linear programming subject to the technical constraint. In addition, ES is charged from both PV and grid, and $P_{PVES}^{n,t}$ could be positive or negative. Thus, the energy price for a positive $P_{PVES}^{n,t}$ is different to the negative case. The PVES owner's profit is given as follows.

$$\mathcal{B}_{PVES}^{n}\left(\boldsymbol{\pi}_{PVES}^{n}, \boldsymbol{\Lambda}_{PVES}^{n}\right) = \max_{\left(\boldsymbol{P}_{Ch}^{n}, \boldsymbol{P}_{Dis}^{n}\right)} \left[\sum_{t=1}^{24}\left(\pi^{n,t} P_{PVES}^{n,t} + \Lambda_{PVES}^{n,t} Q_{PVES}^{n,t}\right)\right] \tag{5a}$$

$$\pi^{n,t} P_{PVES}^{n,t} = \begin{cases} \pi_{PVES}^{n,t} P_{PVES}^{n,t} & if \quad P_{PVES}^{n,t} \ge 0 \\ \lambda_D^t P_{PVES}^{n,t} & if \quad P_{PVES}^{n,t} \le 0 \end{cases} \qquad ,\forall n \tag{5b}$$

$$s.t.\; P_{PVES}^{n,t} = P_{PV}^{n,t} + P_{Dis}^{n,t} - P_{Ch}^{n,t} \qquad ,\forall t,n \tag{5c}$$

$$\begin{cases} 0 \le P_{Ch}^{n,t} \le P_{ch,n}^{max} BS_n^t \\ 0 \le P_{Dis}^{n,t} \le P_{dis,n}^{max}(1 - BS_n^t) \end{cases} \qquad ,\forall t,n \tag{5d}$$

$$E_n^t = E_n^{t-1} + \rho_{ch}^n P_{Ch}^{n,t} - \frac{1}{\rho_{dis}^n} P_{Dis}^{n,t} \qquad ,\forall t,n \tag{5e}$$

$$E_n^{24} = E_n^0 \tag{5f}$$

$$E_n^{min} \le E_n^t \le E_n^{max} \qquad ,\forall t,n \tag{5g}$$

$$\sum_{t=1}^{23} BC_n^t \le \mathrm{N}_{ES} \tag{5h}$$

$$BC_n^t \ge BS_n^{t+1} - BS_n^t \qquad ,\forall n, t = 1,2,\ldots,23 \tag{5i}$$

$$BC_n^t \ge BS_n^t - BS_n^{t+1} \qquad ,\forall n, t = 1,2,\ldots,23 \tag{5j}$$

$$Q_{PVES,n}^{min} \le Q_{PVES}^{n,t} \le Q_{PVES,n}^{max} \qquad ,\forall t,n \tag{5k}$$

where, the constraints are specified for the maximum charging and discharging power (5d), the state of charge and its maximum and minimum boundaries (5e)-(5g), the maximum permitted number of switching back and forth between charging and discharging status (5h)-(5j) for the energy storages, and the maximum and minimum limits of reactive power of PVES unit (5k) which relies on the inverter power factor.

- *Iterative approach for LMP calculation*

In the proposed approach, two aspects should be taken into account: 1) the contribution of each private unit to the power loss and GHG emission reduction; and 2) the DSO surplus profit. In the following, the proposed strategies for considering the mentioned aspects are discussed in detail.

For the first aspect, the sensitivity of the power loss and GHG emission with respect to the changes in active and reactive power of fuel-based DGs and PVES units is evaluated to consider the contribution of each unit to the power loss and GHG emission reduction. This approach is implemented for power loss only in [12-14]. In this paper, the LMP for active and reactive power of the fuel-based DGs and PVES units is defined as follows.

$$\pi_{DG}^{j,t} = \lambda_{ss}^{t} + \left(\frac{\partial Ploss_{new}^{t}}{\partial P_{DG}^{j,t}} + \frac{\partial Em_{new}^{t}}{\partial P_{DG}^{j,t}}\right)\lambda_{ss}^{t} \qquad ,\forall j,t \tag{6a}$$

$$\Lambda_{DG}^{j,t} = \left(\frac{\partial Ploss_{new}^{t}}{\partial Q_{DG}^{j,t}}\right)\lambda_{ss}^{t} \qquad ,\forall j,t \tag{6b}$$

$$\pi_{PVES}^{n,t} = \lambda_{ss}^{t} + \left(\frac{\partial Ploss_{new}^{t}}{\partial P_{PVES}^{n,t}} + \frac{\partial Em_{new}^{t}}{\partial P_{PVES}^{n,t}}\right)\lambda_{ss}^{t} \qquad ,\forall n,t \tag{6c}$$

$$\Lambda_{PVES}^{n,t} = \left(\frac{\partial Ploss_{new}^{t}}{\partial Q_{PVES}^{n,t}}\right)\lambda_{ss}^{t} \qquad ,\forall n,t \tag{6d}$$

The active power of private units can affect both the power loss and GHG emission. However, their reactive power only affects the power loss. This is the reason that the sensitivity of both power loss and emission are considered in the surplus calculation for active power price, and only the sensitivity of power loss with respect to reactive power is considered in the surplus calculation for reactive power price.

Although sensitivity metrics can represent the contribution of each private unit to power loss and GHG emission reduction, the considered LMP (6) cannot be an optimal solution to reach the minimum value for DSO surplus profit. To tackle this problem, an iterative approach is implemented to increase LMP gradually to reach the minimum DSO surplus profit. Furthermore, a triangular function (7) is deployed in the LMP updating process as an accelerator/decelerator factor to control the process in accordance with the amount of surplus profit of the DSO.

$$\alpha = \begin{cases} 1 & ,if \quad \Delta\mathcal{B}_{DSO}^{max} \le \Delta\mathcal{B}_{DSO} \\ \dfrac{\Delta\mathcal{B}_{DSO}}{\Delta\mathcal{B}_{DSO}^{max}} & ,if \ 0 < \Delta\mathcal{B}_{DSO} < \Delta\mathcal{B}_{DSO}^{max} \\ 0 & ,if \quad \Delta\mathcal{B}_{DSO} \le 0 \end{cases} \tag{7}$$

where, $\Delta\mathcal{B}_{DSO}^{max}$ is the maximum amount of surplus profit for DSO obtained by the uniform price approach (i.e. $\pi_{DG}^{j,t} = \lambda_{ss}^{t}$, $\pi_{PVES}^{n,t} = \lambda_{ss}^{t}$, $\Lambda_{DG}^{j,t} = 0$, and $\Lambda_{PVES}^{n,t} = 0,\ \forall j,n,t$).

In the following, an explicit account of the proposed iterative mechanism for the LMP for the private DG owners is provided in the "LMP Calculation Algorithm".

LMP Calculation Algorithm

Step 1: Consider the uniform price (energy price at the substation) for all the DG and PVES buses. The price of reactive power is considered zero [15].

$$\left(\pi_{DG}^{j,t}\right)^{itr} = \lambda_{ss}^{t} \qquad ,\forall j,t$$

$$\left(\Lambda_{DG}^{j,t}\right)^{itr} = 0 \qquad ,\forall j,t$$

$$\left(\pi_{PVES}^{n,t}\right)^{itr} = \lambda_{ss}^{t} \qquad ,\forall n,t$$

$$\left(\Lambda_{PVES}^{n,t}\right)^{itr} = 0 \qquad ,\forall n,t$$

Step 2: Determine DGs' power dispatch according to the bus price by maximizing the DG owner's profit using (4) and (5).
Step 3: Solve the load flow considering DG's power output at each hour. Then calculate the DSO surplus profit using (3).
Step 4: Calculate accelerator/decelerator factor (α^{itr}) in (7).
Step 5: Update the LMP for the private units.

$$\left(\pi_{DG}^{j,t}\right)^{itr} = \left(\pi_{DG}^{j,t}\right)^{itr-1} + \alpha^{itr}\left(\frac{\partial Ploss_{new}^{t}}{\partial P_{DG}^{j,t}} + \frac{\partial Em_{new}^{t}}{\partial P_{DG}^{j,t}}\right)\lambda_{ss}^{t} \qquad ,\forall j,t$$

$$\left(\Lambda_{DG}^{j,t}\right)^{itr} = \left(\Lambda_{DG}^{j,t}\right)^{itr-1} + \alpha^{itr}\left(\frac{\partial Ploss_{new}^{t}}{\partial Q_{DG}^{j,t}}\right)\lambda_{ss}^{t} \qquad ,\forall j,t$$

$$\left(\pi_{PVES}^{n,t}\right)^{itr} = \left(\pi_{PVES}^{n,t}\right)^{itr-1} + \alpha^{itr}\left(\frac{\partial Ploss_{new}^{t}}{\partial P_{PVES}^{n,t}} + \frac{\partial Em_{new}^{t}}{\partial P_{PVES}^{n,t}}\right)\lambda_{ss}^{t} \qquad ,\forall n,t$$

$$\left(\Lambda_{PVES}^{n,t}\right)^{itr} = \left(\Lambda_{PVES}^{n,t}\right)^{itr-1} + \alpha^{itr}\left(\frac{\partial Ploss_{new}^{t}}{\partial Q_{PVES}^{n,t}}\right)\lambda_{ss}^{t} \qquad ,\forall n,t$$

Step 6: Determine the DG power dispatch according to the bus price by maximizing the DG owner's profit using (4), (5).
Step 7: Solve the load flow considering DG's power output at each hour. Then calculate the DSO surplus profit using (3).
Step 8: Check the termination criterion, $\Delta\mathcal{B}_{DSO}^{itr} \le \varepsilon$. If it is satisfied, stop the algorithm; otherwise, go to Step 4.

- *Convergence of LMP Calculation Algorithm*

It is clear that, by increasing the LMP included in the energy price (i.e. $\pi_{DG}^{j,t}$ and $\Lambda_{DG}^{j,t}$ in (4a), and $\pi_{PVES}^{n,t}$ and $\Lambda_{PVES}^{n,t}$ in (5a)), the generation of the private units increases and consequently the negative parts of the (3a) increase. Therefore, the convergence of the algorithm due to the reduction of the surplus profit of the DSO is guaranteed.

III. Performance Evaluation

To verify the effectiveness of the proposed framework, the 118-bus distribution test network [16] with 11 kV substation is employed in the case study. The network is modified by installing 13 fuel-based DG units and 4 PVES units. Fig. 1 depicts the network's single line diagram. More details about the private units are tabulated in Table 1. The average hourly data of PV power generation are obtained from [17].

A. Results and Discussion

In this subsection, the results of three different scenarios including the uniform price approach, sensitivity approach introduced in [12-14], and the LMP scheme are investigated to better demonstrate the integration impact of the LMP on the conventional and sustainable energy resources operation in the distribution network.

The DSO profit for different cases are depicted in Fig. (upper). The DSO profit for the conventional network is \$430,158, which is the profit of purchasing energy from upstream network and selling it to the customers. In addition, it is clear that the DSO profit obtained by the proposed LMP approach is also \$430,158, which is the same as the DSO profit of conventional network (in other words, there is no DSO surplus profit). The DSO profit for the uniform price approach and the sensitivity coefficient approach introduced in [12-14] are \$634,481 and \$514,328, respectively, which means there

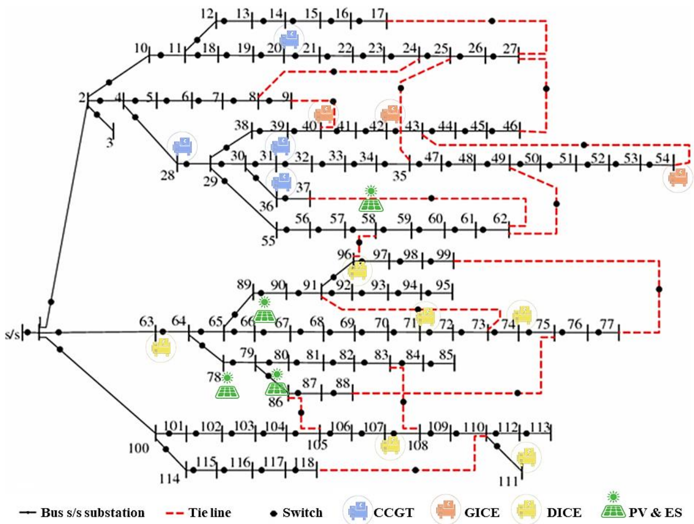

Fig. 1. Single line diagram of 118-bus distribution network

TABLE 1. CHARACTERISTICS OF CONVENTIONAL AND RENEWABLE DG UNITS

DG Units	Type	Capacity	Bus#
Fuel-based	CCGT	all 1000 (kW)	20, 28, 31, 36
	GICE	all 1000 (kW)	40, 42, 54
	DICE	all 1000 (kW)	63, 71, 74, 96, 107, 111
Renewable	PV	1000, 1200, 900, 800 (kW)	58, 66, 78, 86
Energy Storage	Battery	500, 600, 500, 400 (kWh)	58, 66, 78, 86

CCGT: Combined Cycle Gas Turbines
GICE: Gas Internal Combustion Engines
DICE: Diesel Internal Combustion Engines

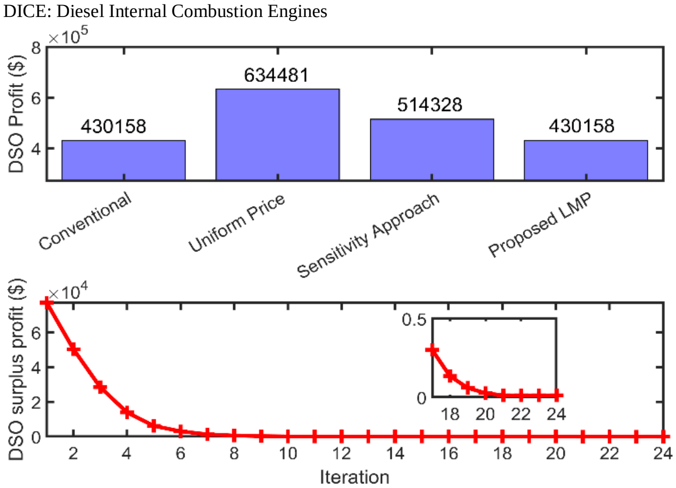

Fig. 2. The DSO profit comparison (upper) and the DSO surplus profit convergence in the propose approach (lower)

are $204,323 and $84,170 as the surplus profit for DSO from private DGs operation in the network, respectively. As already mentioned, in the slave problem, the surplus profit for DSO should be minimized by finding the optimal values for the LMP.

Fig. (lower) shows that the DSO surplus profit converges to zero, which indicates the success of the proposed strategy in order to provide a fair environment in the distribution network price policy. In other words, the DSO considers all the surplus profit obtained from the operation of private units as a LMP for their owners.

Fig. and Fig. depict the LMP values for fuel-based DG units and PVES units, respectively. It can be observed that all the nodal prices are equal to or greater than the market prices. According to these results, at some hours like hours number 1-5, 10-13, and 23-24, the energy price for some private units is the same as the market price. This phenomenon happens due to the negative profit of these units under the presented market price for the mentioned hours. In this regard, the owners of these units prefer to shut down their units to avoid negative profits. At the other hours, the private owners' profit is positive and the DSO calculates the LMP greater than market energy price in accordance to their contribution to the energy loss and GHG emission reduction.

The profit of the fuel-based DG and PVES units in case of the aforementioned approaches is depicted in Fig. . Apparently, the profit of all these units in case of the proposed LMP strategy is greater than the results from the uniform price and sensitivity factor approaches. These increases in the private units' profit are due to the consideration of the DSO surplus profit in locational energy price. As an illustration, the DG units DG7, DG9, DG10 and DG13 at buses #54, #71, #74 and #111 attain about 171%, 117%, 123% and 116% improvement in their profits, respectively. In the worst case, only the DG units DG2 and DG8 at buses #28 and #63 achieve about 8.7% and 5.5% extra profit, respectively. In addition, the best case for PVES units happens for the unit installed at bus #58 with 106% enhancement. However, the unit installed at the bus #66 acquires the minimum 21.3% improvement.

The impact of the proposed LMP approach on energy loss and GHD emission is investigated in the following. The energy loss for both approaches (uniform price and proposed approach) at each hour is depicted in Fig. 6 (upper). At the beginning of the day, due to the low energy cost at the reference bus, the fuel-based DG units are switched off. Moreover, the solar PV panels' power generation is zero at these hours simultaneously. Thus, the energy loss in the proposed approach scheme is slightly increased due to the charging of the ES units. In the middle of the day, due to the power injection of the fuel-based DG units and PV panels, the energy losses are reduced dramatically. In the rest of the day, the PVES power generation is reduced, but due to the high energy price, the fuel-based DG units generate more power. The total daily energy loss for the proposed LMP strategy (6,403.7 kWh) is reduced by 16.04%

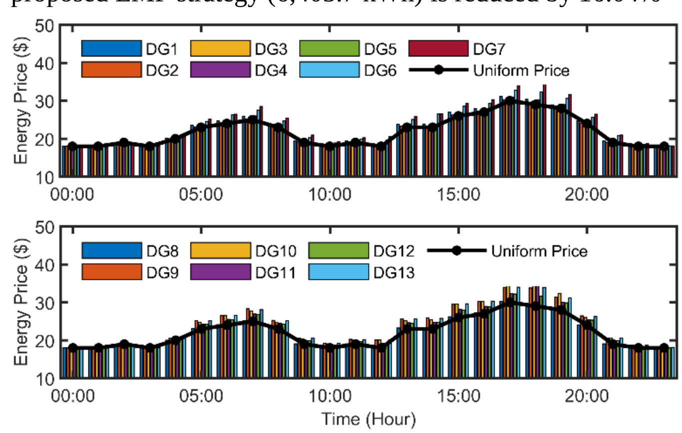

Fig. 3. The nodal prices for each fuel-based DG unit at each hour

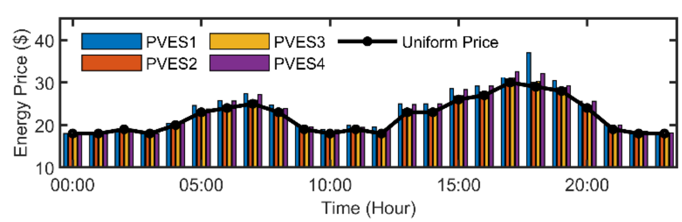

Fig. 4. The nodal prices for PVES units at each hour

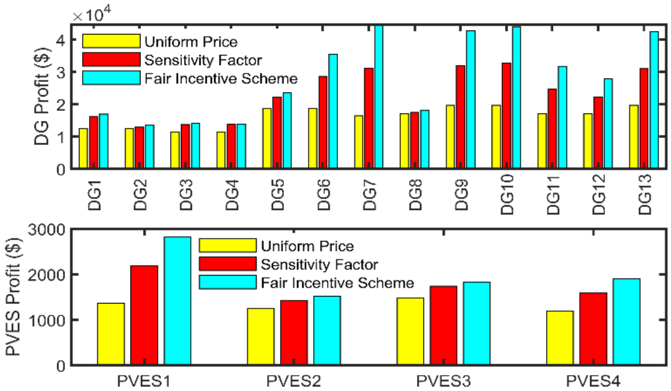

Fig. 5. The graphical representation of private DG owner's profit

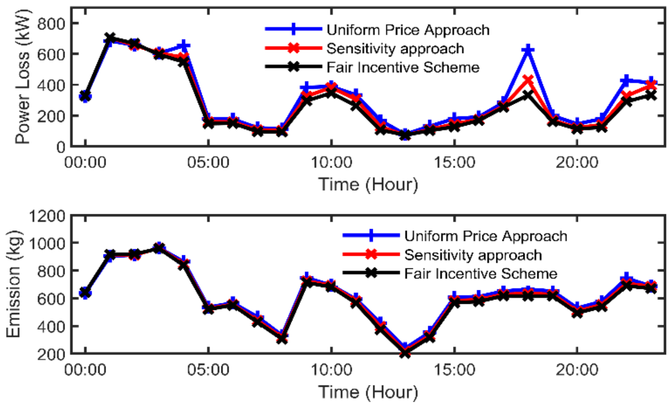

Fig. 6. The amount of energy loss (upper) and GHG emission (lower) for different cases at each hour

and 6.84% in comparison with the uniform price (7,627.1 kW) and sensitivity (6,873.9 kWh) approaches, respectively. Similarly, Fig. (lower) illustrates the GHG emission for all the cases at each hour. According to this figure, the total emission is reduced to 14,314.4 kg by implementing the proposed LMP approach compared with the uniform price (14,946.7 kg) and sensitivity (14,576.8 kg) approaches. It means 4.23% and 1.8% reduction in the GHG emission compared to the uniform price and sensitivity approaches, respectively.

IV. Conclusion

This paper proposed an effective approach to significantly reduce the power loss and GHG emission in distribution networks containing private generation units. An iterative approach is implemented in the proposed approach to calculate the LMP for private units based on their contribution to power loss and GHG emission reduction. To this end, the DSO surplus profit obtained by power loss and GHG emission reduction due to the operation of private units in the network is considered as the financial source allocating LMP for private generation units. The results show 16.04% and 4.23% reduction in power loss and GHG emission, respectively, compared to the uniform price approach without any investment cost. Moreover, compared with the sensitivity approach, there are also a 6.84% reduction in power loss and a 1.8% reduction in GHG emission.

The proposed approach will be implemented in reconfigurable networks in future works, and the uncertainty of PV power generation and load demand will be modeled.

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