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A New Economic Dispatch for Coupled Transmission and Active Distribution Networks Via Hierarchical Communication Structure

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Abstract—Traditionally, the economic dispatch problem (EDP) of the bulk generators connected to transmission networks (TNs) is solved in a centralized dispatching center (CDC) while modeling distribution networks as passive loads. With the increasing penetration levels of distributed generation, coordinating the economic dispatch between TNs and active distribution networks (ADNs) became vital to maximizing system efficiency. This paper proposes a hierarchical communication structure, which requires minimal upgrades to the CDC, for solving the EDP of coupled TNs and ADNs. Based on minimal data transfer between the CDC and distribution network operators (DNOs), the problem is formulated and solved while considering the network losses in both TNs and ADNs. Furthermore, a sensitivity analysis is conducted to assess the effect of the R/X ratio of the distribution lines on the economic dispatch solution and the operational cost of the system. The numerical results demonstrate the effectiveness of the proposed centralized scheme and highlight the significance of considering the network losses of both TNs and ADNs when solving the EDP. The results show that the proposed framework can achieve savings of up to 17.98% by taking into account the network losses of TNs and ADNs.

***Index Terms*—active distribution network, economic dispatch, hierarchical communication, network losses, transmission network.**

I. Introduction

A. Background and Related Works

The integration of distributed generators (DGs) into distribution networks has many pronounced advantages, such as reducing system losses and increasing the penetration levels of renewable resources [1]. Due to the variability and uncertainty of renewable generation, integrating dispatchable DGs allows for increasing the penetration levels of renewable energy based DGs since it boosts the flexibility and controllability of managing active distribution networks (ADNs) and supports the system during contingencies and extreme events. As the penetration levels of dispatchable DGs into distribution networks increase, their interaction with the transmission network (TN) and their potential to enhance the overall system reliability and efficiency increase. Consequently, a remarkable portion of research has been directed toward coordinating the operation of TNs and ADNs. For instance, the ability of ADNs to provide frequency regulation services to TNs is studied in [2]. To enhance the efficiency of system restoration, coordination between the black-start resources in TNs and ADNs is proposed in [3]. A methodology for demand-side management in support of TN operation is developed in [4]. Siting and sizing of energy storage devices in coordinated distribution and transmission systems is proposed in [5]. A voltage stability assessment with the consideration of interactions between TNs and ADNs is conducted in [6]. To optimize the economic operation of the coupled transmission and active distribution system (CTADS), problems such as the unit commitment [7] and economic dispatch have also been considered in the previous literature while taking into account the dispatchable generation in both TNs and ADNs.

Traditionally, the economic dispatch problem (EDP) of the generators connected to TNs is solved in a centralized dispatching center (CDC) while treating the conventional distribution networks as passive loads. After solving the EDP, the dispatching decisions for the next dispatching interval are communicated to the generators. With the increasing penetration of dispatchable DGs into distribution networks, coordinating their operation with dispatchable bulk generators is essential to minimize the total operational cost of the system [8]. However, it is challenging to establish a single CDC that can communicate with all the bulk generators and dispatchable DGs in the system in order to centrally solve the EDP of CTADSs. This challenge is due to the communication congestion and the requirement of high bandwidth communication at the CDC for extending the centralized management of the system [9]–[11].

Several decentralized optimization-based solutions have been proposed for the EDP of CTADSs. A heterogeneous decomposition algorithm is proposed in [8] for solving the coordinated EDP of CTADSs. In this algorithm, the problem is decomposed into a transmission, and several distribution economic dispatch subproblems, and heterogeneous information such as the boundary power and transmission locational-marginal prices are exchanged in an iterative manner to form a decentralized solution algorithm. The method of [8] is extended in [12], producing a generalized master-slave-splitting method to solve a series of central functions of the transmission-distribution coordinated

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energy management such as power flow, economic dispatch, and optimal power flow in a distributed manner that does not require a central coordinator. While competing for presenting more efficient decentralized solutions considering different variants and formulations for the EDP of CTADSs, other decentralized solutions have also been proposed based on multi-parametric quadratic programming [13], alternating direction method of multipliers (ADMM) [14], and analytical target cascading method with diagonal quadratic approximation [15]. In [16], a distributionally robust joint chance-constrained model is developed for the EDP of CTADSs to solve the problem using a fully decentralized optimization scheme based on the asynchronous ADMM. Other decentralized solutions have also been proposed in [17], [18].

B. Research Gaps

To the best of the authors' knowledge, the network losses are not considered in all the aforementioned solutions to the EDP of CTADSs. Decentralized solutions for handling the network losses while solving the EDP have been proposed in [10], [19] but while considering TNs only. The network losses occur in both TNs and ADNs, yet considering these losses are not observed while solving the EDP of CTADSs in the previous literature. Neglecting such losses could accumulate significant monetary losses over time, in particular for large power systems covering a large geographical area and feeding large loads. In addition, all the previously mentioned publications, i.e., [7]–[18], adopt decentralized optimization-based solutions, and no research work is observed toward the expansion planning of existing centralized management and communication infrastructures to cope with CTADSs while avoiding communication congestion and high-bandwidth demands. For systems adopting centralized management structures, the following observations have to be highlighted as the main advantages of proposing centralized solutions to the problem. Extending centralized infrastructures for the EDP of CTADSs could provide solutions requiring significantly lower total costs compared to building new fully decentralized schemes. Moreover, existing CDCs are well-established systems that are capable of solving the EDP, considering features and aspects that are still challenging to be managed using fully decentralized solutions, such as considering the network losses of both TNs and ADNs.

C. Contributions

To fulfill the research gaps, the following contributions are made in this paper.

- The enhancement of existing CDCs to extend their operation for CTADSs by offering a hierarchical communication structure. This structure is designed to have minimal communication links and data transfer between the CDC and generation units, to avoid creating communication congestion at the CDC.
- Unlike previous works, the network losses are considered while solving the EDP of CTADSs. A computationally efficient method is proposed for handling the network losses, which is advantageous in particular for large power systems while considering both TNs and ADNs.

Based on considering the network losses of ADNs, it is observed that the R/X ratio of distribution network lines could significantly affect the total system losses and the economic dispatch of CTADSs. Consequently, a sensitivity analysis is performed to assess the effect of the R/X ratio for the distribution lines on the economic dispatch decisions and the total operational cost.

Utilities adopting centralized management can directly benefit from the above contributions. On the other hand, for other utilities adopting deregulated electricity markets with independent transmission and distribution network operators, the proposed centralized framework presents a benchmark that highlights and assesses the effect of considering the network losses in CTADSs on the economic dispatch solution. This assessment may also be extended in system expansion planning studies while considering the effect of the R/X ratio in ADNs on the economic operation of the system. Furthermore, the proposed framework could be utilized with some adaption by the authority responsible for clearing the electricity markets while assessing the locational-marginal prices and ensuring the most economical operation of the system considering the integrated network losses.

Lastly, we consider balanced medium-voltage ADNs connected to TNs, since it is common to assume balanced operation in medium-voltage primary distribution networks [20], [21]. In these cases, the secondary LV distribution networks are treated as lumped balanced loads [7], [8], [12]–[18].

The paper is organized as follows. The proposed centralized framework and hierarchical communication structure are introduced in section II. The solution of the centralized economic dispatch for a CTADS incorporating the network losses is developed in section III. The simulation results are presented and discussed in section IV, and finally, the conclusion is stated in section V.

II. Proposed Centralized Framework with Hierarchical Communication Structure

The proposed framework aims at solving the EDP of CTADSs in one place, i.e., the CDC. For this purpose, without creating communication congestion or demanding high bandwidth communication, a hierarchical communication structure that requires transferring minimal data between the DGs and the CDC is proposed. The next subsection elaborates on the proposed hierarchical communication structure. Thereafter, the details of the required data transfer through the communication links are discussed in subsection II.B. The developed formulation of the problem based on the aggregated data is introduced in subsection II.C. Finally, the communication of the economic dispatch solution and the summary of the proposed framework are presented in subsection II.D.

A. Proposed Hierarchical Communication Structure

Fig. 1 illustrates the proposed hierarchical communication structure. The required communication links have been divided based on their function into three different classes. Class I communication links represent the communication channels connecting the bulk generators with the CDC. These communication links already exist in conventional power systems and no modifications to these links are required based on the proposed framework. Two other classes, class II and class III, of communication links are required. Class II communication links connect the distribution network operator (DNO) with the CDC.

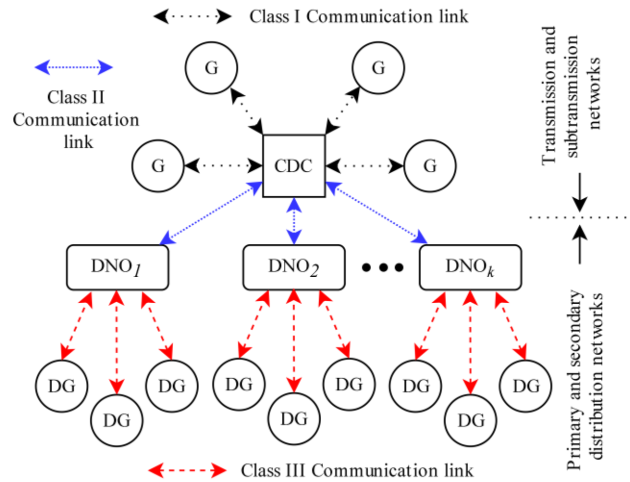

Fig. 1. Proposed centralized framework via a hierarchical communication structure.

DNOs are responsible for managing ADNs. They can be viewed as centralized management units for ADNs. DNOs perform tasks such as forecasting the renewable generation within the ADN, controlling the dispatchable energy resources, and ensuring the power quality and security of supply for the ADN. The framework proposed in this paper aims at establishing cooperation between the CDC and DNOs in order to minimize the total operational cost of CTADSs. Finally, class III communication links connect the DNO with each DG in the ADN. The three classes of communication, indicated in Fig. 1, are bidirectional; however, for the proposed centralized economic dispatch scheme, unidirectional communications directed from the CDC to the bulk generators for class I and directed from the DNO to the DGs for class III are sufficient. Class I communication links already exist in conventional power systems as bidirectional communication links. They are bidirectional based on considering the utilization of these communication links for other related functions, such as solving the unit commitment problem or submitting failure reports from the generators to the CDC. For the same reason, class III is assumed bidirectional. It is important to note that the proposed hierarchical communication structure is primarily used for transferring data at specific points in time, such as before each dispatching interval. This structure uses the most recent system information and forecasts to update the necessary data for solving the EDP effectively. The EDP is then solved within the CDC. This approach differs from decentralized and distributed solution schemes, where the solution computation occurs in a distributed manner based on iterative communications between generators. This latter type of solution scheme requires a highly reliable and extensive communication network. Otherwise, a single communication link failure could make the solution infeasible.

Considering the proposed scheme, temporarily losing a communication channel, such as the one between an ADN and the CDC, is expected to have a negligible effect on the problem solution if certain measures are followed by the CDC and the DNO. In the event of losing the communication link between an ADN and the CDC, one possible measure is to establish a protocol for agreeing on a fixed exchange power between the CDC and DNO during the communication-loss period. This protocol can utilize the historical data of the exchanged power to forecast the exchanged power value for the next dispatching interval, assuming that both the CDC and DNO have the same historical data for the power transfer between them and a common forecasting method. Using this forecasted value, the DNO can then solve a local EDP for the DGs in the underlying ADN, while the CDC can solve the EDP for the rest of the system. The application of this protocol ends once the lost communication is fixed and restored.

The minimal data transfer using the proposed communication structure is discussed in the following subsections.

B. Transferred Input Data

To solve the EDP of CTADSs, each DNO decides on the operational status and limits of the DGs and the expected load of the ADN for the next dispatching interval. This is in line with defining a flexibility area for the dispatchable power from the DGs as in [22]. Thereafter, to submit the minimal data required for solving the EDP of a CTADS, the DNO establishes a set of tuples or a data packet with dimension n_k^{dg}, where n_k^{dg} is the total number of DGs in ADN k. This data packet is denoted as the DG data packet. In this data packet, each tuple is designated as X_j and contains three data elements specific to DG j. X_j is defined as follows:

$$X_j = \langle j \quad Lb \quad Ub \rangle \tag{1}$$

where j is an index for the buses in ADN k, so DG j means the DG connected to bus j, Lb and Ub are the lower and upper limits of DG j, respectively. If the DNO decides that a certain dispatchable DG will not participate in the next dispatching interval, then either no data tuple is created for this DG, or the values of Lb and Ub are set to zero.

It should be noted that Lb and Ub are not necessarily the physical limits of the DG, and the values of these parameters may be adjusted by the DNO to account for technical and security constraints in the distribution network. For instance, due to the estimated variability and uncertainty of renewable generation connected to the ADN during the next dispatching interval, the DNO may decide to reserve a certain capacity of the dispatchable resources to provide a local spinning reserve. This local spinning reserve may also be utilized by the DNO to provide local ancillary services, such as maintaining the voltage within specified limits at specific nodes due to the variability of renewable generation. Estimation of the flexibility area at the transmission-distribution interface has been studied in [22] to determine how much active power is dispatchable within the ADN based on recent system forecasts.

To incorporate the network losses of both TNs and ADNs, another data packet, denoted as the load data packet, has to be defined in addition to the DG data packet. The load data packet has a dimension of n_k^l, where n_k^l is the total number of load nodes in ADN k. Each tuple of this data packet is designated as D_j and contains three data elements as follows:

$$D_j = \langle j \quad P^l \quad Q^l \rangle \tag{2}$$

where j is the bus index of ADN k as mentioned above, P^l and Q^l are the active power and reactive power loads at node j. The total expected load of ADN k is donated as P_k^l. The CDC can calculate the value of P_k^l by summing the submitted values of P^l for each node $j \in$ ADN k. The expected load at each bus of ADN k is equal to the forecasted load minus the expected renewable generation and the fixed dispatchable generation which may not participate in the EDP for the next dispatching interval due to technical or security reasons determined by the responsible DNO. The reactive power load Q^l of each node j is submitted to the CDC since this information is required to estimate the network losses while solving the EDP considering the network losses in ADNs. The network losses can be estimated using Kron's loss formula [23], [24]. This formula requires solving a power flow problem to determine the loss coefficients of the system. Using Kron's loss formula while solving the EDP of CTADSs is discussed in the next section of this paper. Other information, such as the line resistance and the cost coefficients of the generators, required to solve the EDP of a CTADS considering the network losses are assumed to be global information that is known and preserved at the CDC. Consequently, the CDC requires only the update of the allowed operational limits of the dispatchable DGs and the expected loads of ADNs for each dispatching interval to include them in the economic dispatch formulation of a CTADS. Thus, the overall data submitted to the CDC from each DNO through the class II communication link can be expressed by

$$DDNO_k = \langle \frac{X_j\,;\forall j\ \in\ \mathrm{ADN}_k}{D_j\,;\forall j\ \in\ \mathrm{ADN}_k} \rangle \tag{3}$$

where $DDNO_k$, stands for the data from DNO k, concatenates the DG and load data packets. Once all the DNOs submit their data to the CDC, the CDC starts to solve the EDP of the CTADS. The formulation of the EDP is discussed in the following subsection.

C. Problem Formulation

Based on the received and preserved data at the CDC, the proposed formulation for the EDP, while considering the DGs at ADNs and the network losses of both TNs and ADNs, can be expressed as follows:

Minimize:

$$C_T = \sum_{i=1}^{n^G} C_i(P_i^G) + \sum_{k=1}^{n^{AD}} \sum_{j=1}^{n_k^{dg}} C_{k,j}(P_{k,j}^{DG}) \tag{4}$$

Subject to:

$$\sum_{i=1}^{n^G} P_i^G + \sum_{k=1}^{n^{AD}} \sum_{j=1}^{n_k^{dg}} P_{k,j}^{DG} = P^{dl} + P^{loss} + \sum_{k=1}^{n^{AD}} P_k^l \tag{5}$$

$$Lb_i \le P_i^G \le Ub_i \tag{6}$$

$$Lb_{k,j} \le P_{k,j}^{DG} \le Ub_{k,j}, \tag{7}$$

where n^G, n^{AD}, n_k^{dg} are the total number of bulk generators, ADNs, and DGs within ADN k, respectively, C_T is the total operational cost of the CTADS, P_i^G is the generated active power from bulk generator i, $P_{k,j}^{DG}$ is the generated active power from DG j within ADN k, P_k^l is the expected load for ADN k, P^{dl} is the total load that is not integrated by a DNO, such as a load directly connected to the sub-transmission network or a passive distribution network, Lb_i and Ub_i are the lower and upper generation limits of bulk generator i, correspondingly, $Lb_{k,j}$ and $Ub_{k,j}$ are the lower and upper generation limits of DG j within ADN k, $C_i(P_i^G)$ is the cost function of bulk generator i, and $C_{k,j}(P_{k,j}^{DG})$ is the cost function associated with DG j within ADN k. The cost functions $C_i(P_i^G)$ and $C_{k,j}(P_{k,j}^{DG})$ can be evaluated assuming quadratic cost functions [13], [25] as follows:

$$C_i(P_i^G) = a_i + b_i P_i^G + c_i (P_i^G)^2, \tag{8}$$

$$C_{k,j}(P_{k,j}^{DG}) = a_{k,j} + b_{k,j} P_{k,j}^{DG} + c_{k,j} \left(P_{k,j}^{DG}\right)^2, \tag{9}$$

where a_i, b_i, and c_i are the fuel cost coefficients of bulk generator i, while $a_{k,j}$, $b_{k,j}$ and $c_{k,j}$ are the cost coefficients of DG j located in ADN k. Traditionally, the losses of TNs are computed using Kron's loss formula while solving the EDP [26]–[28]. P^{loss} in (5) stands for the total network losses of both TNs and ADNs. An expression for estimating the value of P^{loss} for CTADSs based on Kron's loss formula is provided in the following section of this paper, where a more compact formulation of the problem is introduced.

D. Transferred Solution

The solution of the EDP defined by (4)-(9) is submitted to the bulk generators and DGs using the same hierarchical communication structure. The CDC sends the desired output powers from the DGs to DNO k in a set of tuples with dimension n_k^{dg}, in which each data tuple Y_j is defined as follows:

$$Y_j = \langle j \quad P^{DG} \rangle \tag{10}$$

where P^{DG} is the desired output power from DG j. Once the DNO k receives the DGs' output powers from the CDC through class II communication links, it passes the desired output power to the corresponding DG using class III communication links. The proposed centralized framework for solving the EDP of CTADSs can be put into the following chronological procedures.

Centralized framework for the EDP of a CTADS	
1:	*Each DNO k determines X_j and D_j ($\forall j$) and aggregates these data in a set of tuples, $DDNO_k$ with dimension $n_k^{dg} + n_k^l$.*
2:	*Each DNO k submits the $DDNO_k$ to the CDC through class II communication links.*
3:	*The CDC solves the centralized EDP defined by (4) to (9).*
4:	*The value of P_i^G is sent to generator i ($\forall i$) through class I communication links, and using class II communication links the CDC submits a set of tuples with dimension n_k^{dg}, in which each tuple is defined as Y_j ($\forall j\ \in\ DNO\ k$), to DNO k ($\forall k$).*
5:	*Each DNO k transmits the value of $P_{k,j}^{DG}$ to each DG j using class III communication links.*

III. Solution of the Centralized EDP for CTADSs Incorporating Network Losses

To introduce a computationally efficient method for solving the EDP of CTADSs defined by (4) – (9), the problem is first represented in a more compact form, in which the output power from each bulk generator P_i^G and the output power from each DG $P_{k,j}^{DG}$ are concatenated together in a single vector denoted by $\mathbb{p}$. The length of vector $\mathbb{p}$, expressed as $n^{\mathbb{p}}$, is equal to $n^G + \sum_k n_k^{dg}$. Furthermore, the load of each ADN P_k^l and the remaining loads in the system P^{dl} are summed up to give the total system load P^{TL}, i.e.,

$$P^{TL} = P^{dl} + \sum_{k=1}^{n^{AD}} P_k^l. \tag{11}$$

The power output predicted from renewable sources connected to TNs or ADNs is considered a negative load [29], [30]. For renewable sources within an ADN, the DNO forecasts the output power and adds it as a negative load to the predicted load of the ADN to determine P_k^l. For renewable sources integrated with TNs, the CDC forecasts their output powers and adds them as negative loads while computing P^{dl}. This modeling approach takes into account the use of regulating reserves to compensate for the forecasting inaccuracies during dispatching intervals. When the prediction time horizon is less than six hours, the standard deviation of prediction errors can be less than 0.2, indicating relatively small errors [31], [32]. Therefore, for a prediction time horizon of one hour or less, which is the length of the dispatching interval for the EDP, prediction errors can be neglected [31].

Given P^{TL} and the definition of vector $\mathbb{p}$, the EDP of a CTADS given by (4) to (9), can be expressed in a more compact form as

Minimize:

$$C_T = \sum_{g=1}^{n^{\mathbb{P}}} C_g(\mathbb{p}_g) \tag{12}$$

Subject to:

$$\sum_{g=1}^{n^{\mathbb{P}}} \mathbb{p}_g = P^{loss} + P^{TL} \tag{13}$$

$$Lb_g \leq \mathbb{p}_g \leq Ub_g. \tag{14}$$

In the above formulation, g is an index for all the generators, whether they are bulk generators or DGs, and $\mathbb{p}_g$ stands for the output active power of generator g. In terms of $\mathbb{p}$, P^{loss} in (13) can be represented as

$$P^{loss} = \sum_{g=1}^{n^{\mathbb{P}}} \sum_{m=1}^{n^{\mathbb{P}}} \mathbb{p}_g B_{g,m} \mathbb{p}_m + \sum_{g=1}^{n^{\mathbb{P}}} B_{0g} \mathbb{p}_g + B_{00} \tag{15}$$

where $B_{g,m}$, B_{0g}, and B_{00} are loss coefficients. The loss coefficients in (15) relate the output power from all the generators, bulk generators and DGs, to the total network losses. Equation (15) extends the Kron's loss formula in [23], [26] for CTADSs. The adoption of Kron's loss formula to approximate the system losses while solving the EDP is a common practice in power system literature [26]–[28]. Computation of the loss coefficients takes negligible time compared to the dispatching interval, allowing for them to be updated for each interval or upon the occurrence of a major system change that triggers resolving the EDP [33]. One advantage of Kron's loss formula is its ability to approximate system losses accurately during each iteration of the solution algorithm without the need to solve a power flow problem within each iteration, significantly reducing computational time regardless of the iterative solution technique used in the CDC. This computational time reduction is particularly valuable for large power systems and when formulating the problem for CTADSs. In (12), instead of (8) and (9), $C_g(\mathbb{p}_g)$ can be expressed as

$$C_g(\mathbb{p}_g) = a_g + b_g \mathbb{p}_g + c_g (\mathbb{p}_g)^2. \tag{16}$$

The EDP of a CTADS while considering network losses is defined by (12) - (16). The problem is designated as EDP-CTADS-L, where L indicates considering the network losses. To solve this problem, the Lagrangian function is formed as follows:

$$\mathcal{L}\left(\mathbb{p}_g, \lambda, \overline{\mu_g}, \underline{\mu_g}\right) = C_T + \lambda\left(P^{loss} + P^{TL} - \sum_{g=1}^{n^{\mathbb{P}}} \mathbb{p}_g\right) \tag{17}$$

$$+ \sum_{g=1}^{n^{\mathbb{P}}} \overline{\mu_g}(\mathbb{p}_g - Ub_g) + \sum_{g=1}^{n^{\mathbb{P}}} \underline{\mu_g}(Lb_g - \mathbb{p}_g)$$

where λ is the Lagrange multiplier of the power balance constraint, and $\overline{\mu_g}, \underline{\mu_g}$ are the Lagrange multipliers of the output power limits for the generators. Equation (17) represents an unconstrained optimization problem equivalent to the original constrained one. When $\mathbb{p}_g$ is within the limits, Lb_g and Ub_g, $\overline{\mu_g}$ and $\underline{\mu_g}$ are equal to zero, which eliminates the last two terms in (17). At the optimal solution, the partial derivative of the Lagrangian function with respect to $\mathbb{p}_g$ is equal to zero, i.e.,

$$\frac{\partial \mathcal{L}}{\partial \mathbb{p}_g} = 0. \tag{18}$$

The above condition leads to

$$\frac{\partial C_T}{\partial \mathbb{p}_g} + \lambda \frac{\partial P^{loss}}{\partial \mathbb{p}_g} - \lambda = 0. \tag{19}$$

Since $\frac{\partial C_T}{\partial \mathbb{p}_g} = \frac{dC_g}{d\mathbb{p}_g}$, equation (19) can be rearranged to give

$$\left(\frac{1}{1 - \frac{\partial P^{loss}}{\partial \mathbb{p}_g}}\right) \frac{dC_g}{d\mathbb{p}_g} = \lambda. \tag{20}$$

To this end, it can be noted that the optimal solution implies that the left-hand side of (20) should be equal to a single value, λ, for all the generating units indexed by g. $dC_g/d\mathbb{p}_g$ represents the incremental cost of generator g and $\partial P^{loss}/\partial \mathbb{p}_g$ indicates the incremental network losses for generator g. Considering (15) and (16), the incremental cost and incremental transmission loss are given by

$$\frac{dC_g}{d\mathbb{p}_g} = b_g + 2c_g \mathbb{p}_g \tag{21}$$

$$\frac{\partial P^{loss}}{\partial \mathbb{p}_g} = 2\sum_{m=1}^{n^{\mathbb{P}}} B_{g,m} \mathbb{p}_m + B_{0g}. \tag{22}$$

Substituting by (21) and (22) in (20) leads to

$$b_g + 2c_g \mathbb{p}_g = \lambda\left(1 - 2\sum_{m=1}^{n^{\mathbb{P}}} B_{g,m} \mathbb{p}_m - B_{0g}\right). \tag{23}$$

The linear equations given by (23) represent an undetermined set of equations since the number of unknowns is larger than the number of equations by one. For a given value of λ, (23) can be solved to give the value of $\mathbb{p}_g, \forall g$. Furthermore, the obtained solution should be such that it satisfies the power balance equation (13). Satisfying (13) implies that the power mismatch ΔP given by the following equation is equal to zero.

$$\Delta P = P^{loss} + P^{TL} - \sum_{g=1}^{n^{\mathbb{P}}} \mathbb{p}_g. \tag{24}$$

Obtaining $\mathbb{p}_g$ from (23) and substituting in (24) with $\Delta P = 0$ gives

$$\sum_{g=1}^{n^{\mathbb{P}}} \frac{\lambda\left(1-2\sum_{m=1,m\neq g}^{n^{\mathbb{P}}} B_{g,m}\mathbb{p}_m - B_{0g}\right)-b_g}{2(c_g+\lambda B_{m,m})} = P^{loss}+P^{TL}. \tag{25}$$

Solving (25) requires an iterative process. To establish this iterative process, denote the left term of the equal sign in (25) as $f(\lambda)$, then (25) can be expressed as

$$f(\lambda) = P^{loss}+P^{TL}. \tag{26}$$

Expanding $f(\lambda)$ around an operating point λ_0 using Taylor series expansion while neglecting the higher-order terms provides

$$f(\lambda_0)+f'^{(\lambda_0)}\Delta\lambda = P^{loss}+P^{TL}. \tag{27}$$

Then, from (24), (26), and (27), it can be inferred that

$$\Delta\lambda = \frac{\Delta P}{f'(\lambda_0)}. \tag{28}$$

where $f'(\lambda_0)$ can be evaluated using

$$f'(\lambda_0) = \sum_{g=1}^{n^{\mathbb{P}}} \frac{c_g\left(1-2\sum_{m=1,m\neq g}^{n^{\mathbb{P}}} B_{g,m}\mathbb{p}_m - B_{0g}\right)+B_{m,m}b_g}{2\left(c_g+\lambda B_{m,m}\right)^2}. \tag{29}$$

Using (15), (23), (24), (28), and (29), an iterative process can be developed to solve for the optimal solution of the EDP defined by (12) to (16) as follows where ν is an index for the iterations and ϵ denotes a constant tolerance for the termination condition:

Algorithm 1 Solving the centralized EDP of CTADSs considering the network losses (*EDP-CTADS-L*)

1: $\nu \leftarrow 1$
2: *Set an initial value for* λ^{ν} *and* ΔP^{ν}
3: ***While*** $|\Delta P^{\nu}| > \epsilon$
4: ***Solve*** *(23) with* λ^{ν} *to obtain* $\mathbb{p}_g^{\nu}\ \forall g$
5: ***If*** $\mathbb{p}_g^{\nu} > Ub_g$
6: $\quad\mathbb{p}_g^{\nu} = Ub_g$
7: ***Elseif*** $\mathbb{p}_g^{\nu} < Lb_g$
8: $\quad\mathbb{p}_g^{\nu} = Lb_g$
9: ***Else, End***
10: ***Calculate*** $P^{loss\,(\nu)}$ *using (15)*
11: ***Compute*** ΔP^{ν} *by (24)*
12: ***Evaluate*** $f'(\lambda^{\nu})$ *with (29)*
13: ***Compute*** $\Delta\lambda^{\nu}$ *from (28)*
14: $\lambda^{\nu+1} = \lambda^{\nu} + \Delta\lambda^{\nu}$
15: $\nu \leftarrow \nu + 1$
16: ***End while***

IV. Numerical Results

This section presents a numerical analysis to investigate the effectiveness of the proposed centralized scheme for solving the EDP of CTADSs. First, the utilized indices for assessing the significance of considering the network losses while solving the EDP of CTADSs are presented. Thereafter, two test systems are adopted to evaluate the effectiveness of the proposed scheme and the consideration of network losses.

A. Indices

To assess the significance of considering network losses while solving the EDP of CTADSs, the problem is solved with and without considering network losses. The EDP of CTADSs while considering network losses (EDP-CTADS-L) is defined by (12) – (16). When the network losses are neglected, (13) is replaced by

$$\sum_{g=1}^{n^{\mathbb{P}}} \mathbb{p}_g = P^{TL}. \tag{30}$$

Consequently, the EDP of CTADSs without network losses is defined as

Minimize: (12)
Subject to: (14), (16), and (30).

The above problem is designated as EDP-CTADS-WL, where WL stands for without network losses. The following algorithm is used to compute the monetary saving, expressed by S, and the percentage saving $S\%$ that would be achieved when solving the EDP-CTADS-L instead of the EDP-CTADS-WL for a given system.

Algorithm 2 Computing $S\%$

1: *Solve the EDP-CTADS-L and denote the optimal total cost as* C_T^L.
2: *Solve the EDP-CTADS-WL and denote the optimal dispatch* $\mathbb{p}_g^{WL}$.
3: *Solve a power flow problem while fixing the output power from all the dispatchable generators equal to the values specified by* $\mathbb{p}_g^{WL}$ *except for the slack generator in order to recalculate the output power from the slack generator.*
4: *Replace the output power of the slack generator in* $\mathbb{p}_g^{WL}$ *with the one computed in step 3.*
5: $\mathbb{p}_g^{WL}$ *with the recalculated output power from the slack generator is substituted in (12) to calculate the total cost denoted as* C_T^{WL}.
6: *Calculate* S *for the considered dispatching interval using*
$$S = C_T^{WL} - C_T^L.$$
7: *Compute the percentage saving* $S\%$ *by*
$$S\% = \frac{S}{C_T^L}\times 100.$$

B. Test System T6D2

1) Test System Description

Numerical studies are conducted based on the benchmark CTADS adopted in [7], [8]. This system consists of a six-bus TN connected with two ADNs. The data of this system are given in [7]. Fig. 2 displays the system topology, where a unified numbering for all the system buses and a unified numbering for all the dispatchable generators are used. Fig. 2 also illustrates the application of the proposed hierarchical communication structure, shown in Fig. 1, on the considered CTADS.

2) Sensitivity Analysis Based on R/X Ratio

The value of line resistance is not included in [7] due to neglecting network losses. While assuming values for the line resistance, the effect of changing the R/X ratio in the ADNs on the economic dispatch results has been investigated, and the value of $S\%$ has been determined for different values of the R/X ratio. For medium-voltage distribution networks, the R/X ratios are higher than 1 [20]. They typically assume values between 1 and 3 [34]–[36]. Consequently, the percentage saving $S\%$ in the

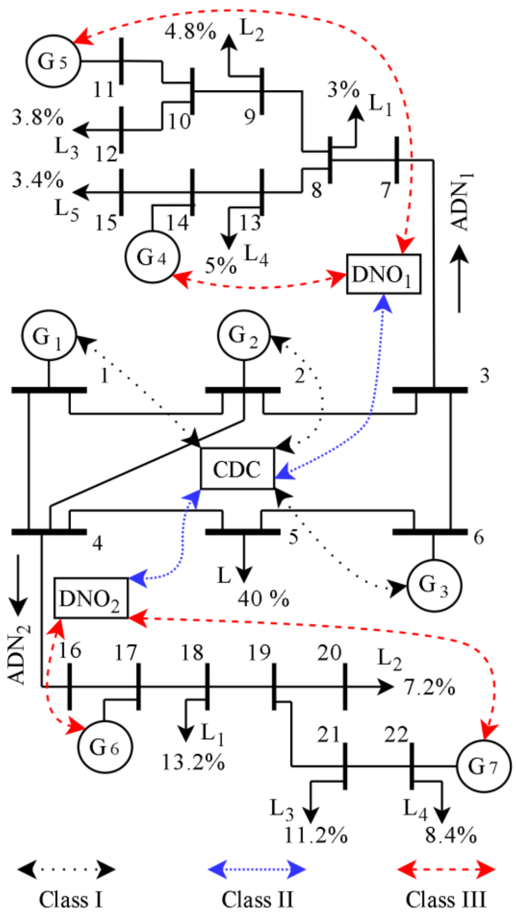

Fig. 2. Six-bus transmission system with two ADNs (T6D2), G_1-G_3 are bulk generators while G_4-G_7 are DGs.

total cost has been evaluated using Algorithm 2, considering five R/X values for the ADNs between 1 and 3. During this sensitivity analysis, the R/X values in the TN have been assumed fixed. The results of this sensitivity analysis are displayed in Fig. 3. The results in Fig. 3 demonstrate that the R/X ratio of ADNs could significantly affect the losses of the system and the monetary saving, which could be achieved when the network losses are considered while solving the EDP of CTADSs instead of being neglected.

3) Solving the EDP

Considering an R/X ratio equal to 2 for all the lines in the ADNs, the total system losses based on solving the EDP-CTADS-L is 11.68 MW, and the total operational cost is 10,149.57 \$/hr. Displaying the optimal dispatch for the bulk generators besides that for the DGs demands plotting a wide range of output powers. So, displaying the output powers from all the generators in one plot can be accomplished based on the normalized values for the output powers. The normalized output power from a generator (bulk generator or DG) can be computed by

$$\mathbb{p}_g^n(\%) = \frac{\mathbb{p}_g - Lb_g}{Ub_g - Lb_g} \times 100. \tag{31}$$

When $\mathbb{p}_g^n = 100\%$, generator g is working at its upper limit (Ub_g), and when $\mathbb{p}_g^n = 0\%$, generator g is generating the minimum output power (Lb_g). Fig. 4 displays the normalized output powers obtained by solving the EDP-CTADS-L. On the other hand, if the EDP-CTADS-WL is solved and the total network

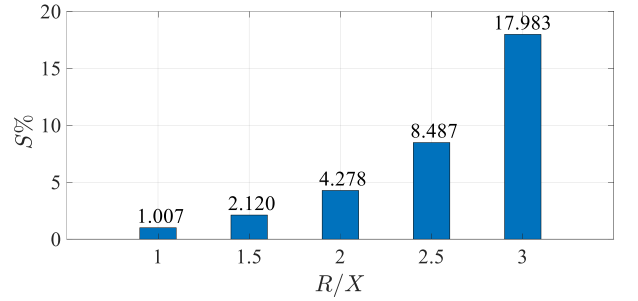

Fig. 3. Percentage saving (S%), due to considering the network losses, as a function of the R/X ratio.

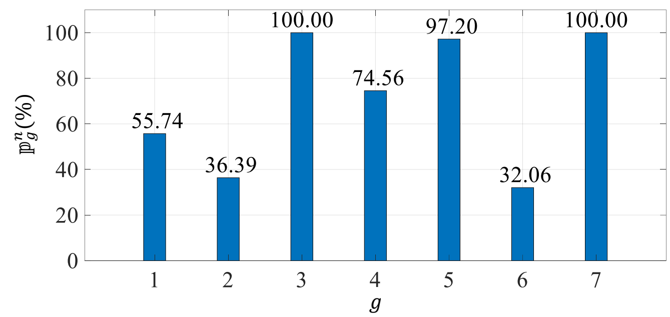

Fig. 4. The normalized output power obtained by solving the EDP-CTADS-L.

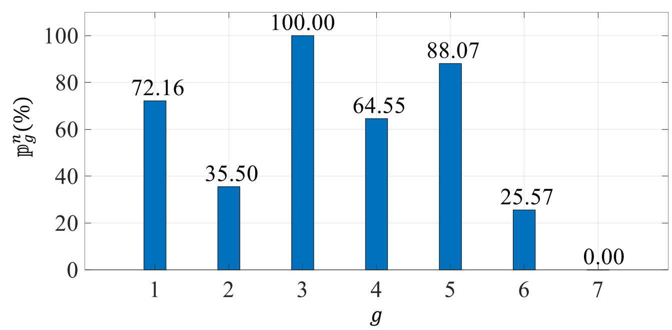

Fig. 5. The normalized output power obtained by solving the EDP-CTADS-WL and recalculating the slack output power ($g = 1$ for the slack generator).

losses have been supplied from the slack generator, the total system losses, in this case, is 22.02 MW, and the total operational cost is 10,583.75 \$/hr. Fig. 5 displays the normalized output powers obtained by solving the EDP-CTADS-WL and recalculating the slack output power as discussed in Algorithm 2. By comparing Fig. 4 and Fig. 5, it can be observed that the output from the last generator (G_7, which is a DG in ADN_2) is 0% in Fig. 5 since the network losses are neglected; however, once the network losses are considered the output power from this generator increased to 100% since the output power from this generator has a significant impact on reducing the system losses.

4) Monetary-Saving Assessment

To shed some light on the daily monetary saving that could be achieved if the problem has been solved while considering network losses instead of neglecting these losses for the adopted benchmark system, the value of S, which is equal to $C_T^{WL} - C_T^{L}$, as defined in Algorithm 2, has been computed for each hour considering a daily load curve obtained from [7], and the obtained values of S have been summed up for the 24 hours. The resultant summation is designated as S_{24}. Fig. 6 displays the variation of the S% for 24 hours based on the considered load curve when R/X = 3 for all the distribution lines in the ADNs. Furthermore,

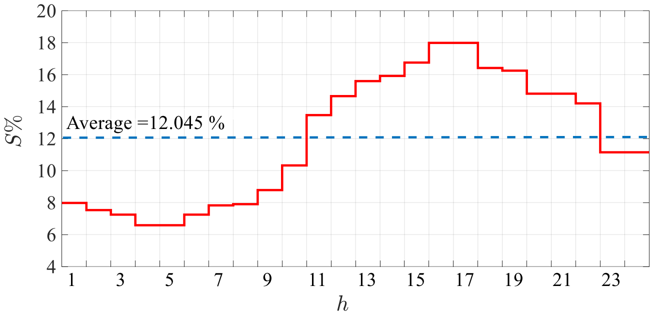

Fig. 6. Percentage saving as the load varies with R/X ratio equal to 3.

TABLE I
VALUE OF S_{avg}, S_{avg}%, AND S_{24} FOR T6D2 CONSIDERING DIFFERENT R/X VALUES IN THE ADNS

		S_{avg} (\$/hr)	S_{avg}%	S_{24}(\$)
R/X RATIO	1	66.17	0.784	1,588.07
	2	273.83	3.172	6,571.92
	3	1,061.40	12.046	25,473.62

the average monetary saving and average percentage saving are denoted by S_{avg} and S_{avg}%, respectively. Table I summarizes the values of theses metrics considering R/X ratios of 1, 2, and 3 for the ADNs. In addition to the monetary saving that can be achieved while solving the EDP, the results in Table I could introduce a significant implication while designing ADNs, since these results relate the R/X ratio of the distribution lines with the economic dispatch and the total operational cost of the system.

5) Extension to the Non-convex EDP

In some power systems, it may be necessary to incorporate practical features associated with bulk generators, such as valve point effects, prohibited operating zones, and multiple fuel options, into the EDP formulation. However, incorporating these features results in a non-convex NP-hard optimization problem. Finding the global optimal solution to this problem is a major concern, and a significant portion of the literature has been dedicated to attaining the global optimal solution for non-convex EDPs. Compared to decentralized solutions for the EDP of CTADS, one prominent advantage of the proposed centralized scheme is that it can easily adapt to handling non-convex formulations of the EDP. The main modification is to change the applied solution method in the CDC. The following example demonstrates solving a non-convex EDP of a CTADS, where the valve point effects are incorporated into the problem formulation. The discrete nature of the control valves in thermal power generation units produces what is designated as valve point effects (VPEs) and affects the cost function of the generating unit, as shown in Fig. 7. To model the VPEs, the cost function in (16) is modified to.

$$C_g(\mathbb{p}_g) = a_g + b_g\mathbb{p}_g + c_g(\mathbb{p}_g)^2 + \left|e_g \sin\left(f_g \times (Lb_g - \mathbb{p}_g)\right)\right|. \tag{32}$$

where e_g and f_g are additional cost coefficients used to model VPEs. The problem formulation is the same as that defined by (12)-(16), which is designated as EDP-CTADS-L, except that (32) is used instead of (16). For the DGs and bulk generators that do not have VPEs, the values of e_g and f_g are set to zero.

Many metaheuristic techniques have been proposed and assessed for solving the EDP with VPEs considering only TNs [25], [37]–[39]. Among the previously proposed techniques, the Gbest-focused ABC algorithm with Levy flights (GFABC-LF)

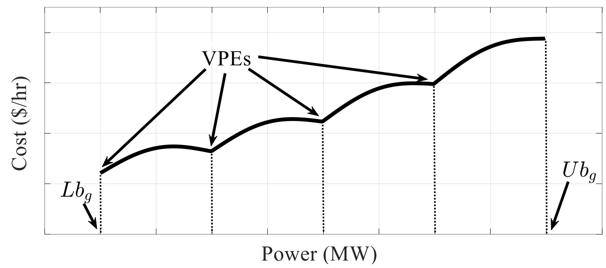

Fig. 7. Non-convex cost function of a unit having VPEs.

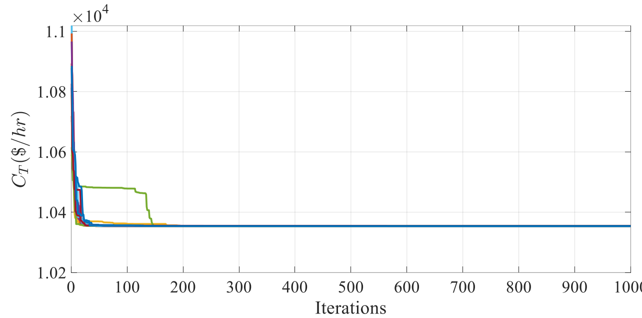

Fig. 8. Convergence curves of the GFABC-LF for 15 runs, while solving the EDP with VPEs for the T6D2 test system.

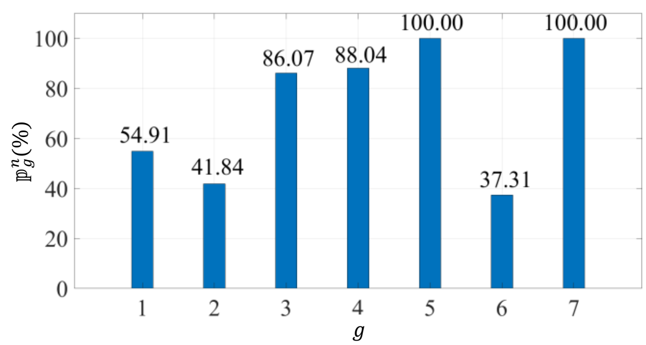

Fig. 9. Normalized output powers obtained by solving the EDP-CTADS-L considering VPEs.

[25] has provided nearly a deterministic solution while finding the global optimal solution for many of the benchmark non-convex EDPs. Consequently, this solution algorithm is adopted in this paper. The VPEs are considered by modifying the cost functions of bulk generators G2 and G3, in Fig. 2. Thereafter, the GFABC-LF has been applied for solving the EDP of the CTADS considering VPEs. Since the GFABC-LF is a metaheuristic technique with a stochastic nature, the problem has been solved 15 times. The convergence curves for the 15 runs are shown in Fig. 8.

For the 15 runs, the GFABC-LF has converged to nearly the same total cost value. The minimum cost value is 10,353.5 \$/hr, and the average cost value is 10,353.9 \$/hr. The normalized values ($\mathbb{p}_g^n(\%)$) corresponding to the best solution are displayed in Fig. 9. By comparing the normalized output powers in Figs. 4 and 9, it can be observed that the optimal output powers from bulk generators G2 and G3 have been changed due to considering VPEs in these units. This change leads to modifications in the optimal output powers of other units, including the output powers of some DGs, such as the DGs identified by G_4, G_5, and G_6 in Fig. 2. The total operational cost has also increased from 10,149.6 \$/hr to 10,353.5 \$/hr due to considering the VPEs.

C. T118-D7 System

1) Test System Description

The test system considered in this subsection comprises the IEEE 118-bus system as a TN connected to seven ADNs. The total number of buses is seven hundred. The total number of generators is 75 (54 bulk generators + 21 DGs). The specifications of the T118-D7 system are provided in [16]. This system is considered to investigate the computational scalability of the proposed scheme and the monetary saving that could be achieved with larger systems.

2) Assessment of Scalability and Computational Efficiency.

The computational time required to solve the EDP-CTADS-L is 1.02 sec. for the T118-D7 system, while the computational time required with the T6D2, where the total number of buses is twenty-two, is 0.71 sec. Therefore, the proposed centralized scheme has efficient scalability regarding the computational time and thus could be applied for power systems with thousands of buses without requiring considerable computational time. Moreover, the proposed centralized scheme does not require extensive communication iterations as required by decentralized schemes. The communication time required to submit a message between two agents in power systems could be less than 0.1 sec. according to the experimental study in [10]. Observing that the communications between the DGs and DNOs are done in parallel and the communications between the CDC and DNOs are also in parallel, it can be inferred that the total communication time required by the proposed scheme can be neglected.

3) Monetary-Saving Assessment

Applying Algorithm 2 for the T118-D7 system provides a value for S% equal to 1.57 %. Although this value may appear relatively small, it reflects a value of S equal to 2,123.4 \$/hr. This value is much higher than the saving value obtained with the T6D2 considering the nearly equal R/X ratio in the ADNs for both systems. This significant hourly saving is because of the relatively high operational cost of the T118-D7 system.

V. Conclusion

A centralized framework for solving the economic dispatch problem of coupled transmission and active distribution networks is proposed. This framework is based on extending the centralized dispatching center via a hierarchical communication structure that enables collaboration between the dispatching center and active distribution network operators while exchanging minimal data through a minimal number of communication links for solving the problem. In addition to the negligible communication time, the numerical results demonstrate the efficient computational scalability of the proposed centralized scheme. Furthermore, an essential advantage of this scheme is its effective handling of network losses in both transmission and active distribution networks while solving the problem. The numerical results show that considering network losses can result in significant monetary savings ranging from nearly 1% to 18% as the R/X ratio of the distribution lines varies between 1 and 3.

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