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Exploring the effects of adaptive reactive support capabilities by DGs in optimal operational scheduling of smart active distribution networks

Sajjad Golshannavaz and Saeed Afsharnia*
School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Tehran, Iran

Abstract. This paper proposes an optimal day-ahead (DA) operational scheduling framework to be implemented in distribution management systems (DMSs) as the core of decision makings in active distribution networks (ADNs). Belonging to the new emerging and prosperous technology namely smart distribution grids, the contextualized ADN is composed of active elements including both renewable-based and conventional distributed generations (DGs) as well as demand side management programs. Also, the information and communication technology (ICT) infrastructures are well-equipped in the network which enriches the distribution system operator (DSO) to have a remote and online control on active elements whenever needed. The proposed day-ahead optimal operational framework firstly schedules the next 24-hour dispatches of DGs, responsive loads (RLs) as well as electricity purchase from wholesale market aiming to minimize the total operation costs. In the first strategy, DGs are supposed to be operated within the mandatory range of reactive support without any financial compensation. Subsequently as an innovative point, the costs of reactive power purchases from both wholesale market and active elements of ADN are judicially included in the scheduling process wherein DGs are contemplated to be utilized in adaptive power factor mode up to a pre-specified minimum value considering financial reimbursements. In contradiction to the conventional fixed pricing mechanisms, a more practical approach for reactive support of DGs is considered and the effect of higher participation of active elements in reactive power provision are thoroughly interrogated in enhancing the economical and technical issues. Also, having a proper control on DGs operating power factor has resulted in extra released capacity which could be exploited to cover the network uncertainties such as wind speed or load variation during a day. The established model is formulated as a mixed integer non-linear problem and solved using binary genetic algorithm. A 33-bus ADN is considered to verify the performance of the proposed optimal operation framework.

Keywords: Smart active distribution networks, distribution management system, distributed generation, adaptive power factor mode, responsive loads, optimal operation scheduling

Nomenclature

Indices and Sets

t, T	Index and set of time intervals
i, j, B, N_{bus}	Indices, set and total number of buses
f, F, N_{br}	Index, set and total number of feeders
s, S	Index and set of substations
g, G	Index and set of DGs
G_i	Set of available DGs in bus i
l, L	Index and set of RLs

Parameters

ρ^{DA}	Day-ahead wholesale electricity price

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*Corresponding author. Saeed Afsharnia, School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Tehran, Iran. Tel./Fax: +98 2161114179; E-mail: safshar@ut.ac.ir.

SU,SD	Start-up and shut-down cost of DG units
a, b, c	DGs cost function coefficients
ρ^{RL}	Contract price for RLs participation
k_q^{DA}	Coefficient for day-ahead reactive power price from wholesale market
k_q^{RL}	Coefficient for RLs reactive power price
k_q^{DG}	Coefficient for DGs reactive power price
C_q^{DG}	Cost function for DGs reactive power production
$P^{\mathrm{D}}, Q^{\mathrm{D}}$	Active and reactive power loads in each bus
Y, θ	Magnitude and phase angle of admittance for feeders
PF^{RL}	Constant power factor for RLs
$S_{\max}^{\mathrm{DA}}$	Substation maximum apparent power capacity
$P_{\max}^{\mathrm{DG}}, P_{\min}^{\mathrm{DG}}$	DGs maximum and minimum active power limit
$Q_{\max}^{\mathrm{DG}}, Q_{\min}^{\mathrm{DG}}$	DGs maximum and minimum reactive power limit
$S_{\max}^{\mathrm{DG}}$	DGs maximum apparent power capacity
$PF_{\max}^{\mathrm{DG}}, PF_{\min}^{\mathrm{DG}}$	DGs maximum and minimum power factor
$P_{\max}^{\mathrm{RL}}$	Maximum power reduction by RLs
$S_{\max}^{f}$	Feeder maximum power flow capacity in MVA
$V_{\max}, V_{\min}$	Maximum and minimum limit on bus voltages in p.u

Variables

$P^{\mathrm{DA}}, Q^{\mathrm{DA}}$	Day-ahead active and reactive power purchase from wholesale market
$P^{\mathrm{DG}}, Q^{\mathrm{DG}}$	DGs active and reactive power dispatch
$P^{\mathrm{RL}}, Q^{\mathrm{RL}}$	RLs active and reactive power commitment
W, X, Z	Binary variables for DGs commitment status, start-up, and shut-down decisions respectively
I	Binary variable denoting the power factor for DGs is beyond the mandatory region
V	Bus voltage
S^{f}	Apparent power flowing feeder f

1. Introduction

Nowadays, most of the societies have been fully aware of the potential energy catastrophes for their next generations [1]. Having an old but not a previously well-recognized history, today, the renewable energy resources (RERs) are getting an eminent role in supporting electricity requirements of societies. In this regard, distributed generations (DGs) and energy storage devices are some new technologies fostering especially inside the territory of distribution companies (discos) to locally provide the consumers demand. On the other hand, due to the economical savings and better asset management, active participation of demand side entities has been evoked and some new concepts such as responsive loads (RLs) are expanding swiftly. Although, this new trend has been in the way of better electrification as well as economical improvements, but they are drastically increasing the complexity of decision makings for distribution system operators (DSOs) [2].

At the moment, there is a common sense both in academia and industry participants that yielding to a more optimal operational strategy along with a better asset management requires a more intelligent network known as "*Smart Grid*" [3]. The recent advances in information and communication technology (ICT) infrastructures such as intelligent electronic devices (IEDs) and remotely smart metering have paved the way for DSOs to realize the smart grid concept. Meanwhile, active distribution networks (ADNs) are known as one of the primarily outlined smart distribution grids. Specifically speaking, ADNs are composed of a strong ICT infrastructure which enables the DSO to optimally remote control of active elements including DGs, RLs and a flexible structure for the network. Although economically/technically beneficial, but the existence of a huge number of influential elements in optimal operational planning of a typical ADN, necessitates a substantial need for a robust and strong decision making unit called as distribution management system (DMS). To be precise, DMS as the throbbing heart of the ADN has been equipped with both efficient load flow algorithms and the essential databases such as the network data. Moreover, it interacts with external and internal operators such as wholesale market to receive the required information. Regarding the day-ahead load pattern and also the natural resources such as wind speed, DMS settles some strong forecasting approaches to have a reliable estimate of these parameters. Having enriched with the foregoing requirements, DMS would initialize to seek for optimal day-ahead operational scheduling of its active elements [4, 5].

So far, some researchers have conducted both technical and practical studies to expand the functionalities of a typical DMS. Algarni et al. [6] have devised a day-ahead operation planning framework which considers the effect of DG units in lowering total power loss in the network. Niknam in [7] has demonstrated the positive effects of DGs in daily Volt/VAr control of distribution systems. However, some brilliant aspects such as the presence of RLs and effective participation of DGs in reactive power provision have not been emphasized in depth. Researchers in [8–12] have made a survey on optimal operation scheduling of distributed energy resources (DERs) in medium voltage (MV) discos. Also in this context, Niknam et al. [13] have proposed a methodology for optimal operational management of distribution networks including fuel cell power plants. Cecati et al. [14] have been on the way of new emerging smart distribution grids. They have implemented an algorithm for DMS as the core of ADN with relatively high penetration of conventional DGs and wind turbines (WTs). This study although establishes some valuable fundamentals in the context of ADNs, however lacks from the participation of RLs and uses a fixed reactive power charging for DGs. Regarding the uncertainties in the natural resources such as wind speed and also consumers demand, some recent studies have suggested the application of two-stage DMS scheduling process. The first stage deals with the day-ahead scheduling of ADN and the second one corrects the assigned optimal values based on accurate data in real-time [15]. However, with an effective forecasting engine, it would be a rational assumption to consider the forecasted values to be enough reliable. In higher level of automations, the ADN may be supplemented with motorized remotely controlled switches (RCSs) which enable DSO to remotely change the running topology of the network by DMS [16]. Also, there is a vast body of published manuscripts focusing on application of reconfiguration in peak-hour loss reduction or reliability enhancement [17–21]. However, application of RCSs in optimal day-ahead operational scheduling of ADNs could be a hot research topic from different aspects which is beyond the scope of this paper.

Based on the aforementioned literature review, this manuscript proposes an effective day-ahead optimal operational scheduling framework to be implemented in DMS. The proposed DMS algorithm strongly endeavors to optimally control the active elements of the ADN including DGs active and reactive power dispatches as well as RLs commitment. In the first stage, DMS treats with the DGs within the mandatory range of reactive power support determined by grid code requirements without any financial compensation. In the second stage, as an innovative point, besides the active power dispatch of DGs and RLs commitment, DMS benefits from the DGs with adaptive power factor mode capability and hence providing adaptive support of reactive power. In this case, monetary reimbursements are made for DGs extra reactive power support beyond the mandatory region. In contradiction to the conventional fixed pricing of reactive power, a practical mechanism for reactive support of DGs is considered and the effect of higher participation in reactive power provision are thoroughly interrogated in enhancing the economical and technical issues. As well, the effect of reactive support capabilities on extra capacity release of DGs is scrutinized in the reserve scheduling problem for covering probable uncertainties such as wind speed or unforeseen load variations. However, the main contributions of the presented work could be listed as follows:

- Proposing a practical model for operating of DGs with adaptive reactive support capability considering financial reimbursement;
- Exploring the technical and economical improvements by the presented algorithm for DMS;
- Highlighting the effect of adaptive reactive support by DGs in extra release of capacity in reserve scheduling problems.

2. Main features of the active distribution network

The ICT infrastructures are now in a fundamental revolution to change into a more sophisticated and advanced systems. This newly enriched schemes such as wireless communication granted through satellites and general packet radio service (GPRS) are smoothing the way to realize a comprehensive controllability on all aspects of engineering [22]. On the other hand, as a result of rapid penetration of ICT systems in electric power distribution networks, ADNs are recognized as one of the earlier concepts established to benefit from the high speed wireless GPRS or fiber optics as the two-way communicating media. These networks are apt to self-organize themselves with an online control capability to enhance the operation of all its interconnected

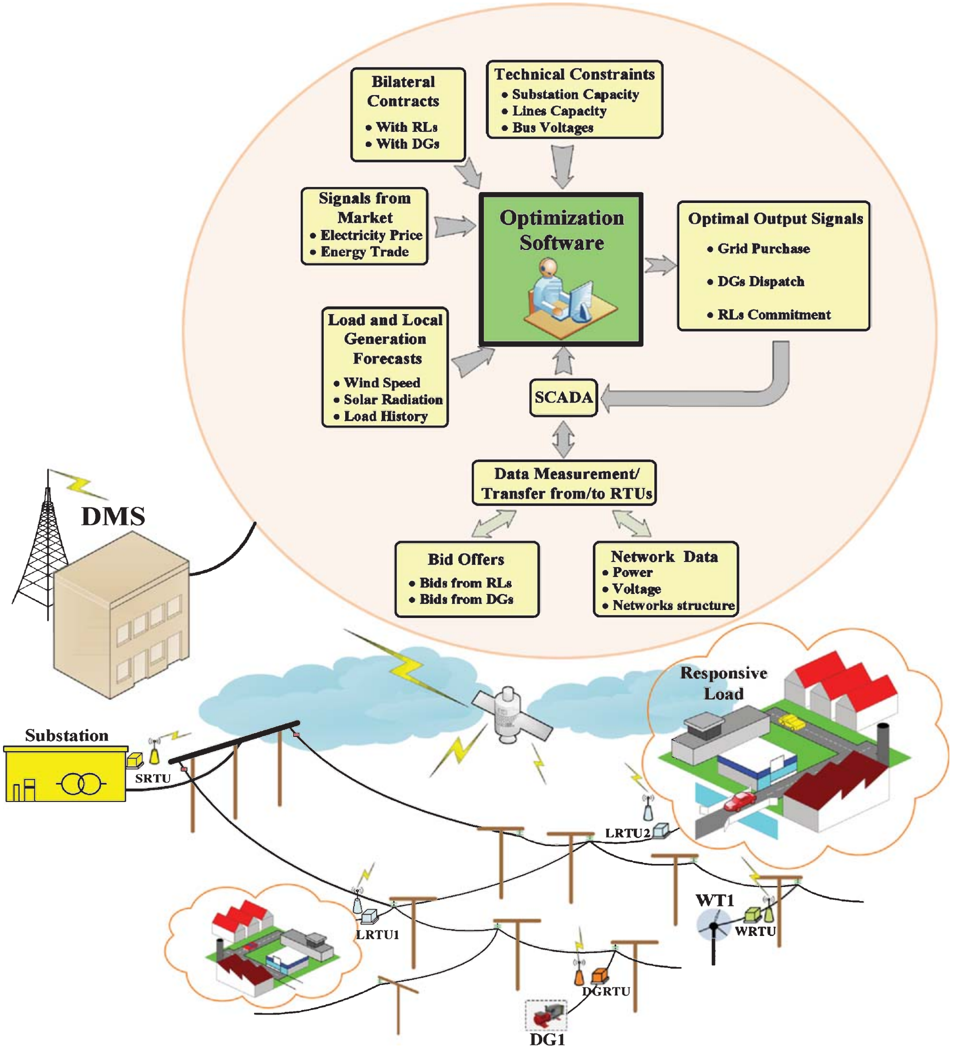

Fig. 1. The contextualized active distribution network.

ingredients. Figure 1 illustrates the visualized ADN, for which the detailed information is addressed in the following.

- Disco encompasses different resources including main grid connection, DGs, WTs, and RLs as the active elements. DMS as the core of ADN is delegated to determine the optimal operational assignments for all elements.
- DSO collaborates with external and internal system operators to receive the market prices and other preliminary information for DMS to make the optimal decision sets. DSO should also be entirely sentient of the network status. Henceforth, distribution remote terminal units (DRTUs) as the infield IEDs are embedded in the territory of ADN. Substation-RTU (SRTU), distributed generation RTU (DGRTU), responsive load RTU (LRTU), and wind turbine RTU (WRTU) are responsible for both remote telemetry with central DMS and implementing online control of active elements [23].
- There may be bilateral contracts signed between DSO with either RLs or DGs to participate in incentive-based programs such as load reduction or generation curtailment. These programs provide influential tools for DSO to cope with the peak hours emergencies. In these programs, the amounts and hours of participation and the paying mechanism are specified exactly.

- DMS also entails the day-ahead load pattern and natural resources forecasting mechanism to accomplish the optimal operational planning. Consequently, well-organized forecasting methods are executed to yield a reliable estimation of consumers demand and renewable generation.
- Being fed by the required data and making use of related database, DMS would operate a regimented optimal load flow program to determine the optimal set-points of control variables for all participants, including optimal hourly grid purchase, DGs dispatch, and RLs commitment.

For each time interval in day-ahead operation, marked out to be one hour, there might be some unexpected forecasting errors as a result of uncertain nature of wind speed or electricity demand which should be concerned. To do so, an intraday optimizer is typically integrated in DMS which in smaller time frames, e.g., every 15 minutes, reschedules its resources based on near real-time data. However, this issue is further than the interest of the current analysis. Though, the effect of proposed model in extra capacity release of DGs has been highlighted demonstrating its capability to cope with the existing uncertainties.

3. Mathematical modeling of the proposed optimal operational scheduling framework

By affording the preliminary forecasts and getting aware of the day-ahead electricity prices, DSO initializes the DMS to seek for the optimal operational scheduling of the ADN. DMS is a set of hardware/software sets where the last part has a more dominant effect in successful decision makings. Hence, the mathematical modeling of the envisaged framework is outlined in the subsequent sections.

3.1. Objective function

Launching a suitable objective function (OF) enables DMS to determine the unknown control variables including grid power purchase from wholesale market, DGs dispatch, and RLs commitment. Meanwhile, DMS would try to precisely regulate the dependent variables in the network such as voltage values under the regulatory rules. In different cases, various objective functions get higher importance for implementation. However, for a disco, the most important one is minimization of total day-ahead operation costs which is formulated here as (1).

$$
\begin{aligned}
&\text{Minimize OF (x,u)} = \sum_{t\in T}\left(\sum_{s\in S}\rho_t^{\mathrm{DA}}P_{t,s}^{\mathrm{DA}}\right. && \text{(a)}\\
&+\sum_{g\in G}X_{g,t}\mathrm{SU}_g && \text{(b)}\\
&+\sum_{g\in G}\left[W_{g,t}a_g+b_gP_{g,t}^{\mathrm{DG}}+c_g(P_{g,t}^{\mathrm{DG}})^2\right] && \text{(c)}\\
&+\sum_{g\in G}Z_{g,t}\mathrm{SD}_g && \text{(d)}\\
&+\sum_{l\in L}\rho_t^{\mathrm{RL}}P_{t,l}^{\mathrm{RL}} && \text{(e)}\\
&+\sum_{g\in G}k_q^{\mathrm{DA}}\rho_t^{\mathrm{DA}}Q_{t,s}^{\mathrm{DA}} && \text{(f)}\\
&+\sum_{l\in L}k_q^{\mathrm{RL}}\rho_t^{\mathrm{RL}}Q_{t,l}^{\mathrm{RL}} && \text{(g)}\\
&+\sum_{g\in G}k_q^{\mathrm{DG}}I_{g,t}\left[b_g\left(S_{g,max}^{\mathrm{DG}}-\sqrt{S_{g,max}^{\mathrm{DG2}}-Q_{g,t}^{\mathrm{DG2}}}\right)\right. && \text{(h)}\\
&\left.\left.+c_g(Q_{g,t}^{\mathrm{DG}})^2\right]\right) && \text{(i)}
\end{aligned}
\tag{1}
$$

In (1), for each time interval t, vectors **x** and **u** contain the control and dependent variables respectively which are given as follows.

$$\mathrm{x}=\left[P_s^{\mathrm{DA}},Q_s^{\mathrm{DA}},P_g^{\mathrm{DG}},Q_g^{\mathrm{DG}},P_l^{\mathrm{RL}},Q_l^{\mathrm{RL}}\right] \tag{2}$$

$$\mathrm{u}=\left[\overline{|V|},\overline{|S_f|}\right] \tag{3}$$

$$\overline{|V|}=\left[|V_1|,|V_2|,\ldots,|V_{N_{bus}}|\right] \tag{4}$$

$$\overline{|S_f|}=\left[|S_1|,|S_2|,\ldots,|S_{N_{br}}|\right] \tag{5}$$

The considered OF in (1) includes different cost components. The cost of purchasing active power from wholesale market and traded through MV substation is given by (a). In the case of excess power generation in the ADN such as by the increase in wind speed specifically at midnights, the presented model, with a small modification, could export the excess power toward the upstream network too. The start-up cost of DGs is represented in (b) where their production costs are included by (c). The shut-down costs for DGs are given in line (d). All DG units are speculated as utility-owned and are centrally dispatched by DSO. Line (e) holds the cost of disco's contracting with RLs in reducing its active power. A concise review of the available literature such as [6] discloses that the reactive power from external grid charges in the order of 5 to 10% of its active counterpart. It should be clarified that the reactive power pricing is itself an intricate issue in newly-born electricity markets. In this regard, the cost of purchasing reactive power from wholesale market is given in (f). With respect to the previous explanations, k_q^{DA} is taken to be equal with 5% for reactive power imported from main grid. Similarly, line (g) reppresents the reactive power costs due to RLs commitment wherein k_q^{RL} is appointed as 10% to promote their cooperation. Regulatory rules and grid code requirements necessitates DGs to provide obligatory reactive support within power factor (PF) ranging from 0.95 lagging to 0.95 leading without any monetary reimbursements [24]. Nevertheless, the emergency conditions in network performance may force a DG unit to run at a lower value of power factor. For this circumstance, DGs are eligible for financial compensations for their extra reactive support. Instead of a fixed pricing scheme, line (h) represents the proposed reactive power charging approach for DGs which is derived in a similar manner as (6) [25].

$$C_{g,q}(Q_g^{\mathrm{DG}}) = k_q^{\mathrm{DG}}\left[C_{g,p}(S_{g,max}^{\mathrm{DG}}) - C_{g,p}\left(\sqrt{S_{g,max}^{\mathrm{DG}^2} - Q_g^{\mathrm{DG}^2}}\right)\right] \quad (6)$$

k_q^{DG} is known as the profit rate of active power generation adjusted between 5 and 10%. This study assumes k_q^{DG} as 10%.

3.2. Constraints

In the minimization process of the proposed OF in (1), DMS verifies continuously the following technical constraints for each trading time interval.

Load Flow Equations in Substations: The effect of DGs in active and reactive power load flow equations in main substations are appropriately taken into consideration as follows.

$$P_{t,s}^{\mathrm{DA}} + \sum_{g \in G_s} P_{t,g}^{\mathrm{DG}} - \sum_{f \in F \& j \in B} P_{t,sj}^{f}\left(V_s, V_j, Y_{sj}, \theta_{sj}\right) = 0 \quad \forall s \in S,\ \forall t \in T \quad (7)$$

$$Q_{t,s}^{\mathrm{DA}} + \sum_{g \in G_s} Q_{t,g}^{\mathrm{DG}} - \sum_{f \in F \& j \in B} Q_{t,sj}^{f}\left(V_s, V_j, Y_{sj}, \theta_{sj}\right) = 0 \quad \forall s \in S,\ \forall t \in T \quad (8)$$

Load Flow Equations in Load Buses: The influential support of DGs and RLs in active and reactive power load flow equations in load buses are properly devised as the sequel.

$$\sum_{g \in G_i} P_{t,g}^{\mathrm{DG}} + P_{t,i}^{\mathrm{RL}} - P_{t,i}^{\mathrm{D}} - \sum_{f \in F \& j \in B} P_{t,ij}^{f}\left(V_i, V_j, Y_{ij}, \theta_{ij}\right) = 0 \quad \forall i \neq S,\ \forall t \in T \quad (9)$$

$$\sum_{g \in G_i} Q_{t,g}^{\mathrm{DG}} + Q_{t,i}^{\mathrm{RL}} - Q_{t,i}^{\mathrm{D}} - \sum_{f \in F \& j \in B} Q_{t,ij}^{f}\left(V_i, V_j, Y_{ij}, \theta_{ij}\right) = 0 \quad \forall i \neq S,\ \forall t \in T \quad (10)$$

$$Q_{t,i}^{\mathrm{RL}} = \tan\left(\cos^{-1}\left(PF_i^{\mathrm{RL}}\right)\right) \times P_{t,i}^{\mathrm{RL}} \ \forall i \neq S, \forall t \in T \quad (11)$$

It is necessary to disclose that the RLs are supposed with a constant power factor as indicated in (11).

Grid Purchase Constraints: To maintain the imported active and reactive power from the external grid to the disco in the range of substations capacity, it is necessary to hold the sequel constraint.

$$\left[\left(P_{t,s}^{\mathrm{DA}}\right)^2 + \left(Q_{t,s}^{\mathrm{DA}}\right)^2\right]^{1/2} \le S_{s,\max}^{\mathrm{DA}} \quad \forall s \in S \quad (12)$$

Generation Limits on DGs: To ensure a suitable dispatch of DGs maintaining their rated active and reactive power capacities, they should keep the following constraints. Meanwhile, as the DGs are applied in adaptive PF mode, they should also meet the allowable range for PF.

$$P_{g,\min}^{\mathrm{DG}} \le P_{t,g}^{\mathrm{DG}} \le P_{g,\max}^{\mathrm{DG}} \quad \forall g \in G \quad (13)$$

$$Q_{g,\min}^{\mathrm{DG}} \le Q_{t,g}^{\mathrm{DG}} \le Q_{g,\max}^{\mathrm{DG}} \quad \forall g \in G \quad (14)$$

$$\left[\left(P_{t,g}^{\mathrm{DG}}\right)^2 + \left(Q_{t,g}^{\mathrm{DG}}\right)^2\right]^{1/2} \le S_{g,\max}^{\mathrm{DG}} \quad \forall g \in G \quad (15)$$

$$PF^{\mathrm{DG}}_{t,g} = \frac{P^{\mathrm{DG}}_{t,g}}{\left(P^{\mathrm{DG}}_{t,g} + Q^{\mathrm{DG}}_{t,g}\right)^{1/2}} \quad \forall g \in G \qquad (16)$$

$$PF^{\mathrm{DG}}_{g,\min} \leq PF^{\mathrm{DG}}_{t,g} \leq PF^{\mathrm{DG}}_{g,\max} \quad \forall g \in G \qquad (17)$$

RLs constraints: This constraint ensures that the allocated amount of RLs by DSO would be limited in the pre-specified ranges determined in the contract for hour *t*.

$$0 \leq P^{\mathrm{RL}}_{t,l} \leq P^{\mathrm{RL}}_{t,l,\max} \quad \forall l \in L \qquad (18)$$

Flow Limits on Feeders: For distribution feeders, the power transform is limited by the maximum apparent power given in MVA.

$$\left[\left(P^{f}_{t,ij}\right)^{2} + \left(Q^{f}_{t,ij}\right)^{2}\right]^{1/2} \leq S^{f}_{\max} \quad \forall f \in F \quad (19)$$

Bus Voltage Limits: The radial structure of the distribution networks may come upon the DSO with voltage quality problems such as low voltage magnitudes for end consumers. Also, there may be voltage proliferation problems evolved due to higher power injections by DGs. In order to obviate these concerns, the forgoing constraint corroborates acceptable voltage magnitudes in all buses.

$$V_{\min} \leq \left|V_{t,i}\right| \leq V_{\max} \quad \forall i \in B, \forall t \in T \qquad (20)$$

3.3. Computation technique applied in optimization

The implemented day-ahead operational scheduling framework establishes a mixed integer non-linear problem. The proposed strategy has been solved using binary genetic algorithm (GA) in MATLAB/Simulink platform. GA as a comprehensive search technique imitates the biological selection process in which the most eligible parents in a population would be more likely to stay alive and duplicate their genetic code to the forthcoming offsprings. This process is known as evolution practice executed by specific operators explicitly crossover and mutation. The iterative generation and evaluation process makes GA capable of carefully scanning the search space and then finding the optimal solutions [26].

3.3.1. Problem codification

The codification process is referred to establishing a possible set of solutions represented in the form of one chromosome. A chromosome in GA is in fact the set of unknown variables of the considered problem seen as the genes. The implemented coding strategy for optimal operational scheduling for each time period is depicted in Fig. 2. The proposed chromosome includes three real number strings. The first and second strings are responsible for DGs active and reactive power scheduled values respectively, and the third string corresponds to the participation percent of RLs for the next 24-hour.

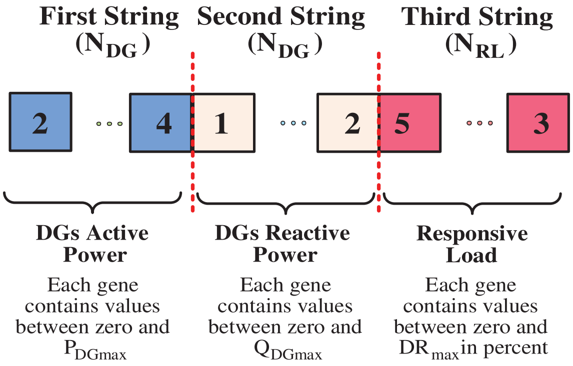

Fig. 2. Structure of the proposed chromosome.

3.3.2. Crossover and Mutation

In this stage, some of the chromosomes are randomly selected. Then from stochastically elected points, known as crossover points (CPs), the selected chromosomes are shared with each other to generate new offsprings. Hence, each offspring would contain a piece

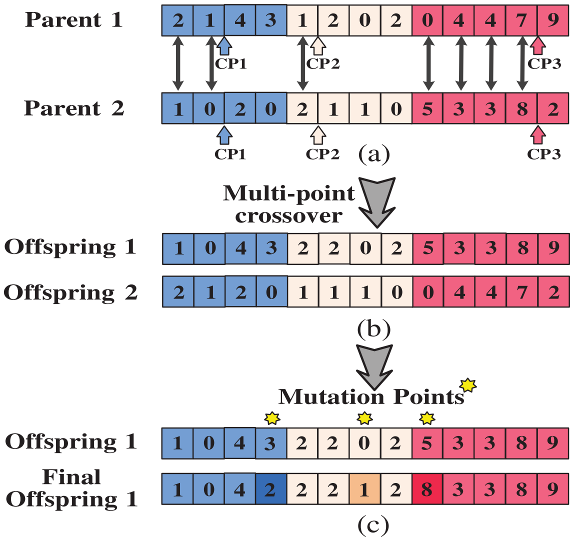

Fig. 3. (a) Selected parents, (b) crossover process (c) mutation process.

of its parent's coding pattern. In the following, some of the genes in the newly offsprings are altered randomly to keep the stochastic nature of reproduction process and also to expand the search space effectively. Figure 3 illustrates the multi-point crossover and mutation process. Several runs with different rate values for crossover and mutation rate have been performed for this study. Although there was not so remarkable difference, the best results were achieved with population size of 50, crossover rate equal to 0.5 and mutation rate adjusted at 0.01 respectively. However, raising the crossover rate might speed up the convergence procedure of the optimization problem.

4. Numerical results and test case evaluation

The purpose of this section is to assess the efficiency of the proposed day-ahead operational scheduling framework through some numerical studies. In the succeeding sections, the system specifications as well as the utilized data acquired from international utilities are provided. Subsequently, the main assumptions and different case-studies are established and then analyzed in-depth.

4.1. System specifications

Figure 4 exhibits the studied ADN which is extracted from modified single line diagram of the well-known IEEE 33-bus 12.66 kV radial distribution system. The basic data for the considered system can be found in [27]. The network consists of four diesel-based DGs at nodes 8, 13, 16, and 25 whose features are settled previously by [28] and are presented in Table 1. In order to improve the DGs overall efficiency, they should be activated approximately in more than 25% of their ratings [29]. Hence, a minimum limit for DGs active power provision is included in the proposed methodology. Otherwise, they will not be switched on. Moreover, the leading or lagging minimum PF for DGs is determined as 0.85 to include their participation in ancillary adaptive reactive power support. Also, three 3MW WTs as the renewable-based DGs are supplemented in the network at nodes 14, 16, and 31. DSO has signed some supportive contracts with five largest loads at nodes 8, 14, 24, 30, and 32 as the RLs with constant PF. These loads could be declined by DSO up to 10% of their actual loads during normal and peak hours including 8 to 24. The price of 1MW decrease in power by RLs is speculated as 115 $/MW as asserted in the contract. Node 1 is the only link between disco and the wholesale market as the main substation. With respect to Fig. 4 and with the aim of equipping the network with a strong online controlling capability for all infield active elements, different DRTUs are installed in ADN. The situations for the date July 16, 2013 at NYISO's PJM have been utilized as the day-ahead scaled wholesale market prices and forecasted load to evaluate the proposed scheduling framework. In this regard,

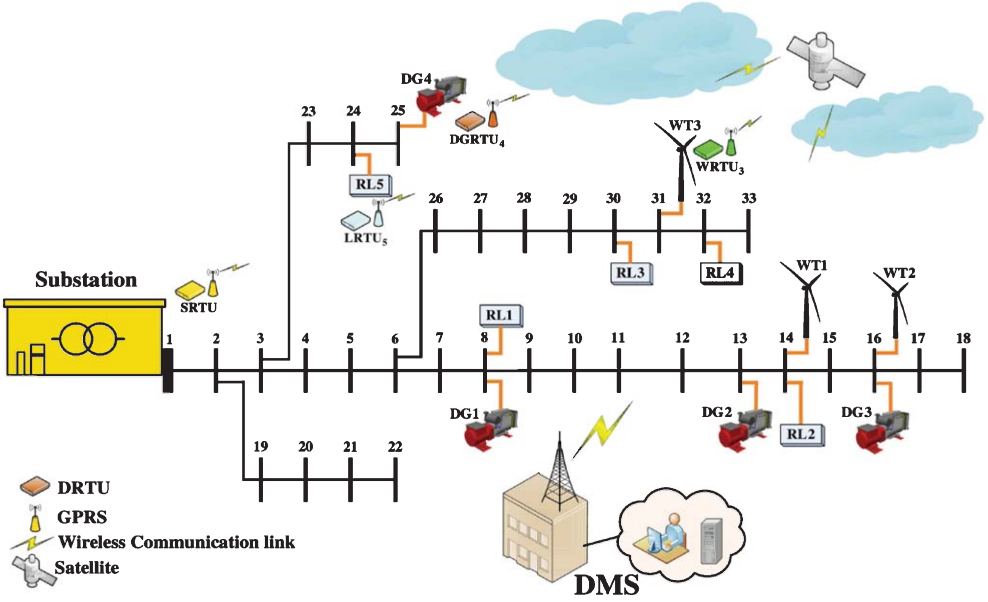

Fig. 4. Contextualized IEEE 33-bus active distribution network.

Table 1
Cost coefficients and technical data for DG units

Unit	Cost function coefficients					Technical constraints	
	a_g (\$)	b_g (\$/MW)	c_g (\$/MW^2)	SU_g	SD_g	$P_{g,min}$ (MW)	$S_{g,max}$ (MVA)
DG1	27	79	0.0035	15	10	1	4.12
DG2	25	87	0.0045	15	10	1	3.53
DG3	28	92	0.0045	15	10	1	3.53
DG4	26	81	0.0035	15	10	1	4.83

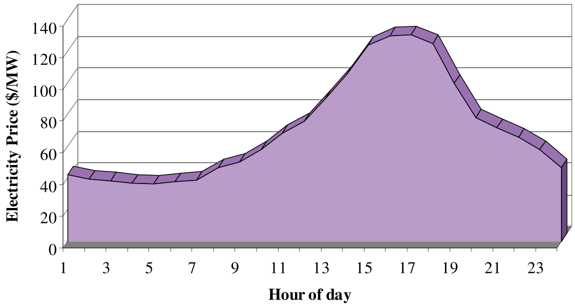

Fig. 5. Day-ahead wholesale electricity prices.

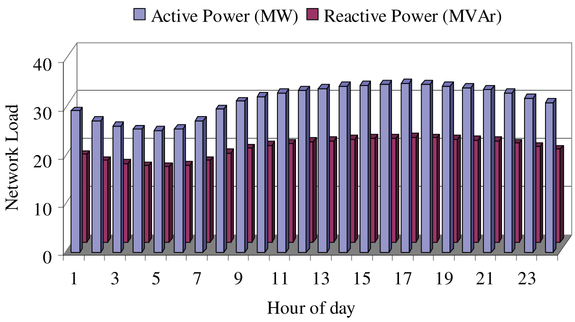

Fig. 6. Forecasted day-ahead load profile of the ADN.

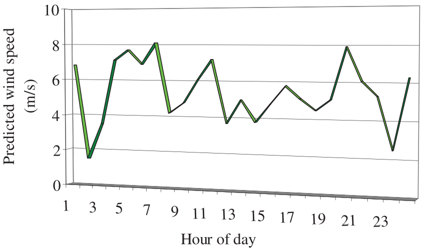

Fig. 7. Forecasted hourly wind speed profile.

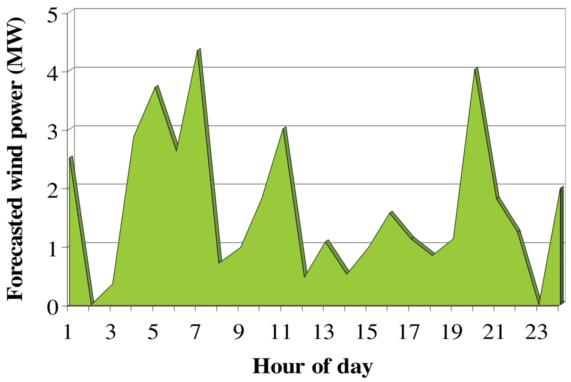

Fig. 8. Forecasted hourly power generation by WTs.

Figs. 5 and 6 show the electricity prices and the network total load for the next 24-hour respectively.

Considering renewable generations, wind speed forecasts and the resultant produced power by WTs are addressed in Figs. 7 and 8 respectively. The geographical conditions have been taken analogous for three WTs. Thus, the wind speed profile is also taken similar.

4.2. *Assumptions in brief*

Herein, the most important assumptions considered in assessing the test cases are listed as below:

- There is a rather truthful forecasting engine for wind speed and load profiles. Thus, the predictions are assumed to be enough reliable;
- The self-required reactive powers for WTs are provided by both local converters and reactive compensators without any need to the distribution grid. Hence, WTs are applied only for active power injections without reactive provisions;
- As the operation costs of WTs are negligible, it can be safely taken equal with zero;
- DGs are modeled with adaptive PF capabilities to share them in higher reactive support, if necessary;
- All active elements are centrally dispatched and controlled by DMS through infield DRTUs;
- Modern bidirectional digital relays are evolved in the network to ensure a safe protection.

4.3. *Test cases and comparative discussions*

To investigate the efficiency of the implemented operational framework, two different cases have been devised and explored thoroughly. Subsequently, a comparative discussion is conducted to underline the promising improvements.

4.3.1. Optimal operation scheduling of ADN with DGs in mandatory region for reactive power

This case is referred to as Case-I where DSO has limited capability for reactive power provision by DGs. The minimum leading or lagging power factor is set as 0.95. In this scenario, DMS would determine the optimal grid purchases, DGs dispatch and RLs commitment.

4.3.2. Optimal operation scheduling of ADN with DGs in adaptive power factor mode

The second case which is indicated with Case-II, benefits from DGs with extended reactive support region where financial compensation is also considered. In this scenario, again DMS would determine the optimal grid purchases, DGs dispatch, and RLs commitment.

4.3.3. Comparative discussions and promising improvements

The performance of the proposed operational scheduling framework in optimal dispatching of DGs and grid purchase is demonstrated in Figs. 9 to 11. As it is seen from Fig. 9, in Case-II, DGs can provide higher reactive power support than Case-I especially in normal load hours namely 8 to 14 and 21 to 24. For these hours, Fig. 10 demonstrates that there is a decline in active power generation by DGs and hence the grid power purchase has increased somehow. This performance has resulted in a more economic saving that will be discussed in the following. It is also worth noting that although DG2 is an expensive unit than DG4, but as it is sited in the most impressive part of the network, has a substantial influence in network performance and consequently is more dispatched by DMS. DG1 has the lowest production cost and with respect to its siting location, it could have a higher technical impact. Thus, it is the most scheduled unit during the day. In the off-peak hours, including 4 to 7, as the grid electricity price is lower than the DGs production costs and the network load is in its lowest value, DMS does not switch on DGs and DSO interacts solely with external grid in both cases. Also Fig. 11 shows that in these hours, the amount of active power purchased from external grid in both Cases-I and II would remain constant. This figure also demonstrates the increase in purchased active power from external grid specifically for the hours with normal load. For the peak hours namely 15 to 19, wholesale electricity prices are rather higher than DGs production costs. Hence, if more attention is paid on Figs. 9 to 11, it can be observed that in both cases, DGs are mainly participating in active power generation and DMS has decreased its reactive power purchase from DGs even in the adaptive PF mode represented by Case-II. Hence, there would be a slight change in purchasing active power from grid. In this context, Fig. 12 (a) and (b) are

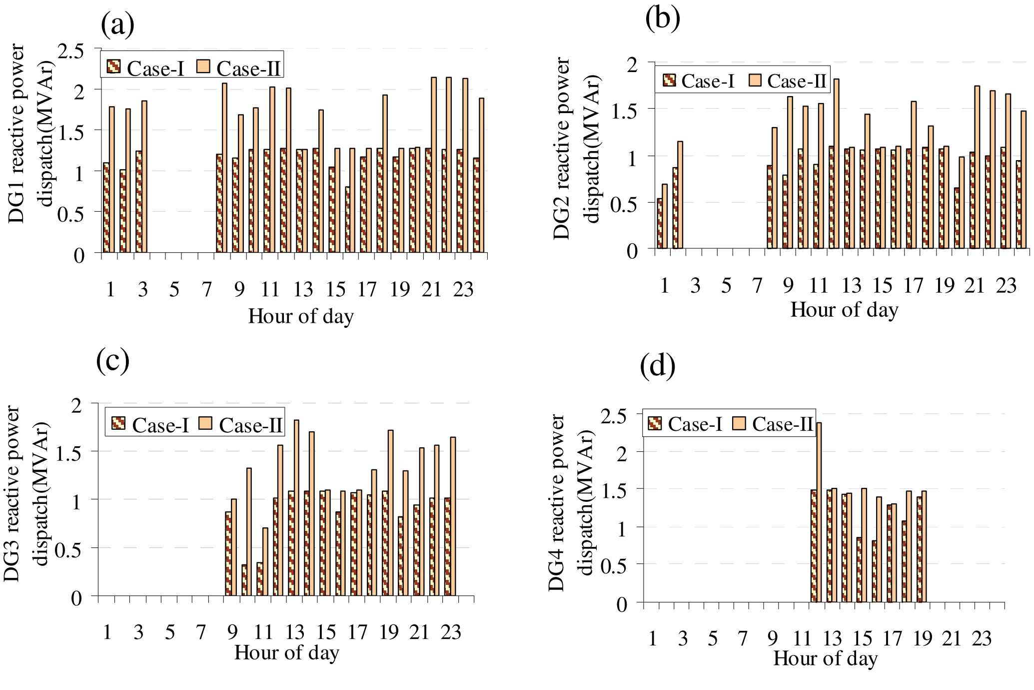

Fig. 9. Scheduled reactive power from DGs.

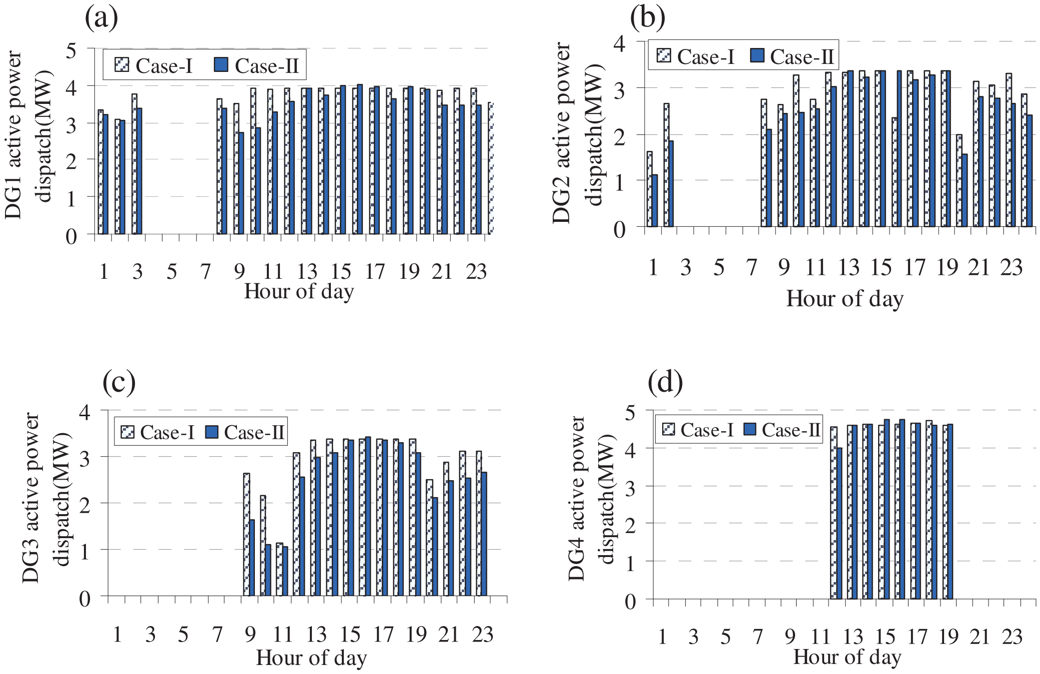

Fig. 10. Scheduled active power from DGs.

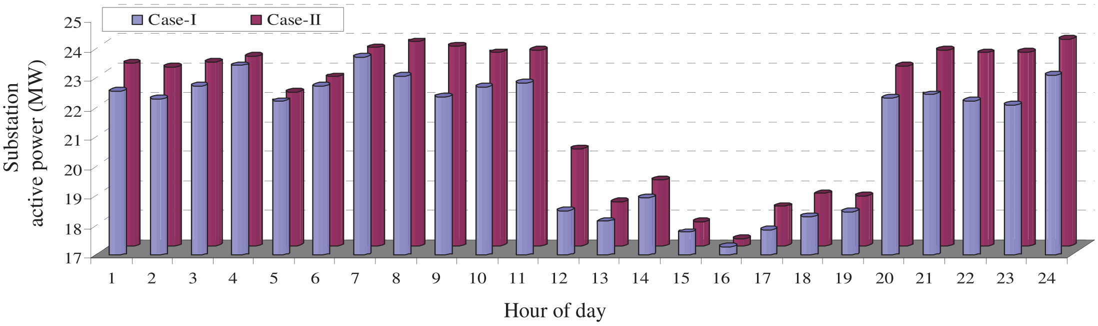

Fig. 11. Active power purchased from grid and imported through substation.

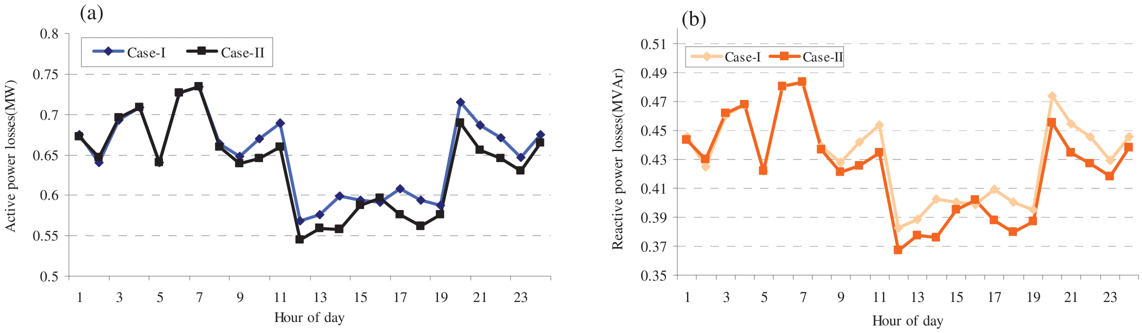

Fig. 12. (a): Total active power losses in the network, (b): Total reactive power losses in the network.

illustrating the network active and reactive power losses respectively. As discussed earlier, in Case-II, DGs are producing more reactive power as well as participating effectively in active power generation compared with Case-I in normal and peak load hours. Hence, both the active and reactive power losses reduction would be remarkable for these hours.

Figure 13 exhibits the effect of adaptive reactive support capabilities by DGs in daily released capacity of DGs. It can be observed that in the Case-II, an extra 3.45 MVA, i.e. 2.16%, is provided as released capacity which could be applied for covering wind speed or load uncertainties. Hence, application of DGs with adaptive reactive support capability would be impressive in the reserve scheduling problems too.

Figure 14 exhibits the day-ahead RLs commitment in Case-II. It is so clear that the DMS is mainly dispatching the RLs at the peak load hours. For the other hours, RLs are only partially scheduled to satisfy the technical constraints of the network. There is a similar discussion for RLs in Case-I too.

It will be fruitful to provide a brief discussion on economic features of both Cases-I and II. The total daily operation costs in Case-I is obtained as 56467.63 $ while this amount for Case-II with adaptive PF is determined as 56149.39 $. This result shows 0.56% reduction in total daily costs of disco. As the huge number of discos comprises the building blocks of power systems, any slight decrease in total cost would have a great influence and vital importance. It can be inferred that in Case-II, operating DGs in adaptive PF mode, although has resulted in some monetary compensations, would result in both technical improvement such as power loss minimization and economic improvements represented in total daily cost reductions. The obtained results certify the outperformance of the proposed optimal operational scheduling framework for ADNs in the context of smart distribution grids.

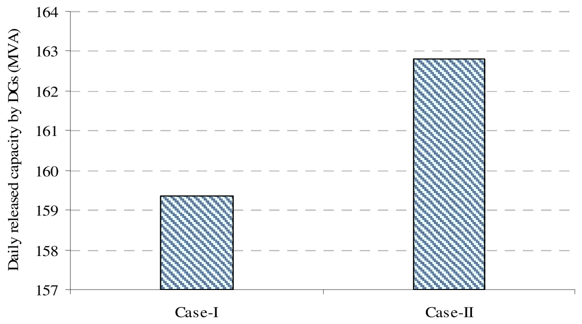

Fig. 13. Effect of adaptive reactive support by DGs in released capacity.

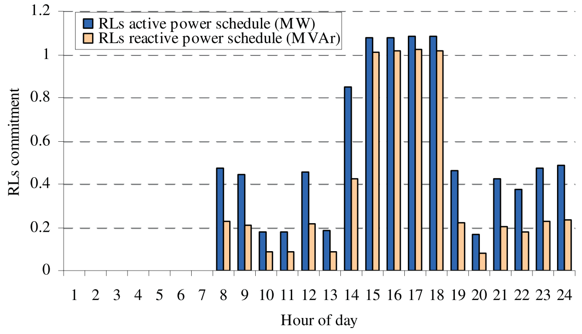

Fig. 14. Apparent power reduction by RLs.

5. Conclusion

An optimal day-ahead operational scheduling framework has been developed effectively for ADNs. Besides the grid power purchases, the proposed methodology has intended the use of DGs in adaptive PF mode along with RLs to manage the network requirements. By analyzing the developed case studies, it can be inferred that incorporating DGs in adaptive PF mode has resulted in higher reactive power support for the network especially for the hours with normal load. For the peak-load hours, the wholesale prices are going to rise where the role of DGs changes to be mainly on active power generation. Consequently, the reactive power support from DGs both in Case-I with mandatory roles and Case-II with adaptive PF mode is nearly the same. In both Cases I and II, DMS appropriately interacts with RLs at the pre-specified hours to effectively cope with the network requirements particularly at peak-hours. It is deduced that the suitable application of DGs and RLs could be beneficial in power loss reduction throughout the day. It is worth noting that although DSO is imposed by some monetary reimbursements in adaptive PF mode for DGs and also for reactive power provision by RLs, the proposed methodology has resulted in a more economic savings. These observations certify the outperformance of the proposed strategy in optimal operational scheduling of ADNs in smart grid contexts.

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