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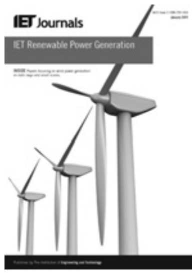

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Indirect coordination of electricity demand for balancing wind power

Tokhir Gafurov, Milan Prodanovic

Unit of Electrical Systems, Institute IMDEA Energía, Avenida de Ramon de la Sagra 3, 28935 Móstoles, Spain
E-mail: tokhir.gafurov@imdea.org

Abstract: High penetration of wind energy in modern power systems led to an increase in the balancing requirements, especially in load-following and unit commitment time frames, which only further compromised the overall reliability and efficiency of electricity supply. One of the possible solutions to address this critical balancing capacity issue is the application of demand response schemes on regular basis for matching electricity consumption and production. This study examines the existing applications of demand response in the given area and proposes an alternative approach based on a proactive dispatch of large industrial consumers by using indirect coordination. The candidate industries suitable for the implementation of the new demand response scheme are sought for and presented. The usefulness and the performance of the proposed arrangement operating as a regular balancing mechanism have been evaluated and demonstrated in several test-case scenarios by applying simplified Monte Carlo simulations.

Nomenclature

The electric power values are normalised by the installed total wind capacity, which also applies to the derived parameters:

- i — subscript defining time-step of the day
- Δt_{DR} — demand response (lead) time
- Δt_{BAL} — time interval used for imbalance estimation
- L, L_{da} — actual and day-ahead planned consumer loading for given time-step
- E_L, $E_{L,da}$ — actual and day-ahead planned daily demand
- G, G_{da} — actual and day-ahead forecasted wind generation for given time-step
- ε — error in wind power forecast for given time horizon (normalised by the installed wind capacity)
- I_0, I_1 — difference between day-ahead forecasted and actual values of wind power before and after demand response
- $\sigma(X)$ — standard deviation of parameter X (same unit as X)
- ΔL_{reg} — relative regulation capacity of consumer
- $R_{\pm DR}$ — operating reserve provided by demand response (positive or up-regulation is equivalent to generation increase, negative or down-regulation – to generation decrease)
- $R_{\pm res}$ — residual operating reserve requirements
- η_{reg} — regulation (balancing) efficiency of demand response
- ΔR_{reg} — reduction in balancing needs by using demand response

1 Introduction

In modern power systems, growing penetration of wind energy increases the risk of demand–supply mismatch leading to higher-operating reserve requirements. This, in turn, reduces the overall efficiency of the electricity supply, as the regulation energy is normally provided by producers with high marginal costs and the required balancing capacity is allocated based on robust, but sub-optimal, unit commitment solutions.

Negative impact of wind generation on the power system balancing depends on the concerned time frame, and as shown in [1, 2] it is not of primary importance on the level of frequency regulation. This is because at high production volumes and geographical dispersion the wind variability is considerably smoothed within the time scales of up to several minutes. The adverse effect of wind on maintaining balance in the grid remains strong however at longer time horizons corresponding to load-following (10 min to several hours) and unit commitment scheduling (hours to days). The influence on the latter tends to be more significant, which is usually explained by the frequent need of intra-day corrections to the unit commitment in order to accommodate the varying wind production without compromising the security margin [3, 4].

Currently, one of the primary technical solutions suggested for improving grid flexibility in matching demand and supply is demand response (DR). In general, DR is defined as change in electricity consumption realised in accordance with economic and technical signals reflecting the present or expected conditions in national power supply. Among various DR schemes, as illustrated in Fig. 1, regular-use DR (RU-DR) is a relatively new tendency. In contrast to

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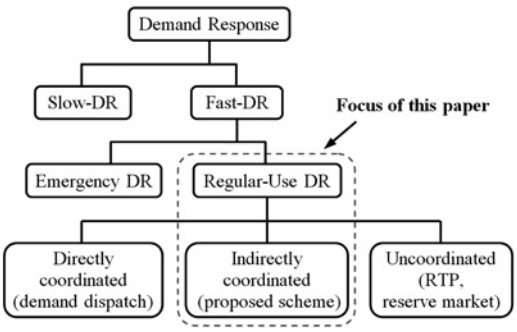

Fig. 1 *Adopted classification of DR techniques, based on the time scale of consumer response, usage frequency and coordination level*

[Traditionally, DR programmes are categorised by reliability or economic criterion, but the distinction between these two groups has been blurred during recent years [5, 6]. The new taxonomy is used to demonstrate the main difference between the proposed and existing DR schemes.]

slow-DR and emergency-DR, RU-DR implies continuous adjustments in electricity demand and when adequately implemented can be treated as an alternative balancing mechanism.

This paper addresses the power regulation issue at load-following and unit commitment time frames and focuses on RU-DR applications for reducing the operating reserve needs caused by increased wind penetration. Based on the analysis of the current developments in the given area, we propose an alternative approach for employing RU-DR as an effective balancing instrument. General feasibility of implementation of the new RU-DR technique among industrial consumers is demonstrated through the literature review. The performance of the proposed regulation procedure and its dependence on the selected load and wind characteristics are investigated by numerical simulations.

2 Existing approaches in RU-DR

RU-DR programmes can be employed with or without coordination of individual consumers. In the first case, the popular trend is application of direct load control, whereas in the latter case it often involves retail real-time pricing (RTP) and load bidding in the reserve market. A brief critical analysis of the given RU-DR techniques is provided below.

2.1 Retail RTP

RTP on consumer side basically consists of dynamic retail pricing linked to the current or anticipated wholesale market prices. Its advantage is that it provides symmetric treatment of load and generation in the electricity market which in turn improves the coupling between electricity wholesale and retail and thus increases the overall demand elasticity [7].

Despite technical feasibility, extensive implementation of retail RTP however is still impeded because of its potential negative implications on both physical and market layers of electricity supply. From a consumer perspective, the main shortcoming is inherently high volatility of RTP scheme, which makes it difficult to evaluate adequately its potential costs and benefits in the long term. This agrees with the general tendency of retail customers to prefer the conventional flat-rate supply contracts or financial hedges [8]. On a system level, the disadvantage of RTP is related to the uncertainty about the consumer behaviour when being exposed to dynamic electricity prices. As shown in the studies [9–12], RTP distorts natural load diversity and creates the risk of synchronised response of the consumers to the changes in electricity prices which in turn can lead to unexpected load peaks during the day. To prevent this, the tools employed in planning of the power system operation would need to be revised taking into account the altered load diversity, which is not straightforward however without profound knowledge about the consumer response to RTP signals. This knowledge is also essential in choosing adequate architecture and designing the special mechanisms of electricity markets which would guarantee market stability in case of large-scale use of retail RTP [13].

2.2 Balancing market

Electricity reserve market plays an important role as a general framework to organise balancing services during regular and emergency conditions of power system operation. Traditionally, these services are provided by the generators; however, during the recent years there has been an increasing tendency also for the load participation [14].

There is no doubt that RU-DR can be implemented through the reserve market, but the question here is to what extent one can rely on the market framework, in general, to accomplish the power regulation. Among the fundamental concerns in this case is design of the balancing market [15]. The task of choosing adequate market architecture and developing its underlying mechanisms is highly challenging in view of the following aspects:

- The market operation is subject to numerous technical constraints as its clearing takes place within a short period before the actual system dispatch.
- Intrinsically high and volatile prices for the balancing services create interest in having large imbalances in the system and encourage financial speculation.
- Coordination of the reserve market operation with other market layers is not straightforward. In addition to the above-mentioned technical restrictions, the difficulty is related to the issue of the price sign [15], which creates the risk of inappropriate bidding by the market participants.

2.3 Demand dispatch

The term 'demand dispatch' refers to a relatively new application of direct load control in residential and to a certain extent commercial sectors which is aimed to achieve high flexibility in total electricity consumption by coordinating large number of interruptible appliances. Unlike the previous RU-DR techniques, demand dispatch assures predictability and availability of the response, which are among the primary criteria outlined by the system operator for DR [16]. Despite its attractiveness as a potential power regulation mechanism, large-scale implementation of demand dispatch is undermined by the two important drawbacks:

- Massive coordination of residential and commercial loads faces significant technical challenges, such as development of strong information and communication infrastructure and design of reliable multi-level and distributed control system [12, 17]. And even if succeeded, the resultant complexity of

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the control layer would certainly reduce the reliability of power supply [18].

- Direct load control implies interference with design and operation of consumer facility (equipment, appliances, the building envelope etc.) which can lead to its sub-optimal performance [19]. This is explained by the simple fact that the system operator evaluates the facility operation only based on its electricity consumption, whereas from the consumer perspective the facility overall efficiency is determined by numerous aspects among which electricity usage is often of secondary importance.

3 Indirect coordination of electricity demand

3.1 General requirements

In this paper, we propose an alternative RU-DR arrangement which could be used as a power regulation mechanism by the balance-responsible party (BRP). The new scheme basically involves indirectly coordinated proactive dispatch of large and flexible consumers with the purpose of ameliorating the negative impact of wind intermittency on power system operation.

Considering the downsides of the current developments, the proposed RU-DR technique is characterised by four general requirements. Firstly, the objective is defined as to compensate the deviations of the actual values of net load (demand minus wind production) from its day-ahead forecasts, because at system scale the main operational difficulties are not caused by the net load variability, but by its poor predictability. This condition represents the primary feature that differentiates the new scheme from the existing ones.

Secondly, the main participants of RU-DR programme are large consumers with flexible electricity demand (LCFED), which are capable of providing balancing services to the grid on a regular basis without compromising performance of its own facilities. The intention in this case is to achieve the same total regulation capacity by grouping fewer consumers and thus reduce the complexity of DR coordination and eliminate the need for large communication infrastructure.

Thirdly, stable financial remuneration is provided for the retail customers offering RU-DR services. Predictability of future payments is essential to enhance commitment of the existing consumers and attract the new ones. In case of the latter, the advantage is explained by the fact that fixed pricing allows performing appropriate cost-benefit analysis of RU-DR programme, especially when it requires additional investments aimed at improving the flexibility in electricity consumption. The other positive aspect here is that the financial risks related to uncertainties in the regulation costs are undertaken by the party who is in fact responsible for maintaining the balance in the grid and possesses the resources to adequately predict and reduce the involved risks.

And finally, responses from individual LCFEDs are coordinated indirectly, that is, with a clear separation in controls of power grid and consumer facility. In other words, BRP does not control consumer appliances, it only sends demand modification requests and consumer decides how to achieve the required adjustment in its electricity consumption. The resultant advantage is that DR programme can employ relatively simple control architecture, aggregate customers with rather different demand structures and allow more efficient operation of the consumer facilities. Naturally, it is assumed that a special bilateral agreement exists which provides strong incentives (e.g. in the form of discounted electricity tariffs) to follow the BRP regulation requests and penalises any deviations.

Table 1 Main design features and advantages of the proposed RU-DR scheme

Design features	Advantages
aimed at compensating the forecast errors in renewable production	serves as an alternative system; balancing mechanism
against direct load control and RU-DR in residential sector	
focus on large and flexible consumers; separation in controls of power grid and consumer loads	simple control architecture; reduced requirements for communication infrastructure; efficient operation of consumer facilities; aggregation of customers with different demand structures
against RU-DR based on RTP and reserve market	
coordination by BRP	reliability and predictability of RU-DR;
fixed financial remuneration	reduced investment risks for RU-DR programme participants

The given underlying conditions (design features) and the corresponding advantages of the new RU-DR arrangement are summarised in Table 1.

3.2 Power regulation procedure based on the new RU-DR arrangement

The system balancing by the proposed RU-DR scheme is done in the following steps:

1. *Day-ahead planning*: On the day before the operating day LCFED specifies the expected (planned) amount of daily electrical energy for the next day and its flexibility constraints. BRP based on this data and also considering the day-ahead predictions of the net load and availability of the conventional reserves determines for each consumer the optimal day-ahead loading schedule (DALS).
2. *Time-step-ahead correction*: During the operating day at each control interval, BRP updates the net load forecasts for the next time-step and in case of deviations from the day-ahead plan requests load modifications; otherwise LCFED follows the planned consumption profile.

The overall data flow diagram for the power regulation process including the described RU-DR procedure is shown in Fig. 2. Within the proposed balancing approach, the DALS optimisation represents a key and novel measure. Since the consumption of LCFEDs has to be included into the planning of system operation, the regulation capacity available on each day from RU-DR is defined by the difference between the scheduled loading profile and its upper/lower limits. Therefore the objective here is to distribute during the day the planned electricity demand of LCFEDs so that the potential balancing needs (costs) are minimised for the given net load uncertainty range. As a result of the required coupling with unit commitment, the final mathematical problem is rather complex and its detailed analysis is left for future work. In the numerical investigation, presented in Section 5, the DALS optimisation is simplified by focusing only on the wind production uncertainty and assuming the same costs and

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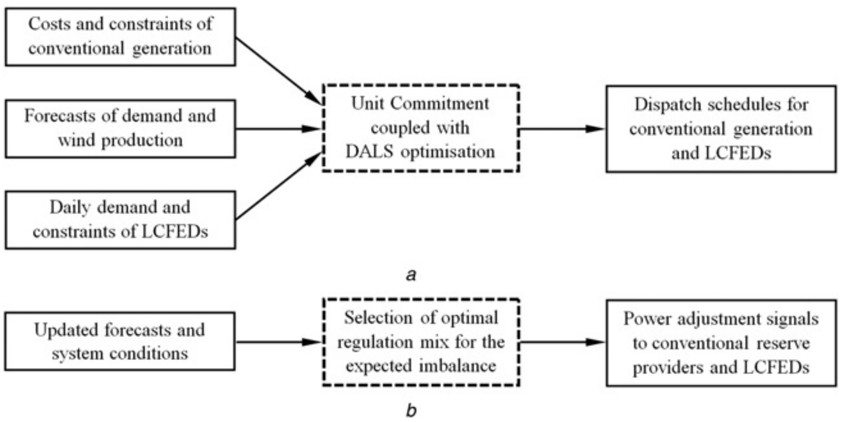

Fig. 2 *Simplified data flow diagram for the system balancing process including the new RU-DR scheme*
a Day-ahead time horizon
b Time-step-ahead time horizon

uniform daily availability for both positive and negative operating reserves.

4 Consumers suitable for implementing the new RU-DR technique

As the proposed RU-DR programme requires large and flexible retail customers, its primary application area is considered to be industrial sector. This is explained by high-energy intensity and price-elasticity of industrial consumers. As a matter of fact, in EU countries industry has the largest share in the total electricity demand approaching an average of 36% [20], with electricity costs ranging from 3 to 90% of the total running costs [21]. Since industrial customers form only a small fraction of the total electricity customers, this leads to significantly higher-consumption rate per consumer and per unit value added and thus higher price-responsiveness of industry compared with residential and commercial sectors.

In view of an inherent variety of industrial processes, it is expected that their flexibility in electricity consumption and thus suitability for the new RU-DR scheme differ largely. For identifying the industries with the highest potential for the application, it is essential to consider the three DR enabling factors: load curtailment, self-generation and storage.

Load curtailment represents the typical measure of demand response and for this reason often DR potential is estimated based on the load capacity available for shedding or shifting. The main industries considered to have large potential in load curtailments are summarised in Table 2. It is important to note that high utilisation factor and complexity of the equipment impede frequent usage of load shedding in industry, which means that RU-DR can be rather limited when based only on the load manipulations.

Alternatively, self-generation grants industrial customers maximum flexibility to regulate their electricity demand from the grid. Notable share of auto-production on industrial sites is indicated by the fact that electricity constitutes only a quarter of the final energy consumption of European industry with the remaining share coming primarily from fossil fuels [20]. Here, it is important to distinguish between the mono- and co-generation. The former is widely employed by industrial consumers as a back-up because of stricter requirements on reliability of

Table 2 Main industries with large potential in load curtailments

Sources/regions	Industrial sub-sectors
survey of 9 companies in the UK [21]	chemicals, steel, industrial gases, ceramics, water
survey of 70 companies in Austria [22]	paper and cardboard, steel, cement, chemicals
survey of 14 companies in Finland [23]	pulp and paper, basic metals, basic chemicals
survey of 207 companies in CA, US [24]	forest products, food, basic chemicals, industrial gases, aerospace products, high-tech test labs, fabricated metal products, cold storage, water

[The original studies cited here focus primarily on load shedding and load shifting. The latter however often implicitly reflects the potential in storage. Use of self-generation for DR is mentioned only in [21].]

their power supply. In certain cases, however, mono-generators are used not only for reserve, but also to cover part of the electricity demand [21]. For instance in the US industries of petroleum, chemicals and forest products, electricity generated by power-only-sources accounts for ~0.3 and 1% of the total and industrial retail sales volumes, respectively [25].

Compared with mono-generation, usage of combined heat and power (CHP) in industry is significantly higher which is explained by strong dominance of the heating demand and enhanced economic viability of co-generation. As estimated in [26, 27], the total share of the existing industrial CHP in the EU is 4.6%, whereas the unexploited potential from the selected industries is 14.3% of the global electricity demand (Fig. 3).

Finally, storage offers an additional effective means of adjusting the grid consumption without load shedding. Since electrical storage technologies are not yet economically viable, it is reasonable to consider the use of relatively low-priced non-electrical storage instead to achieve flexibility in electrical consumption [28]. From this perspective, thermal energy storage is of special interest considering widespread employment of industrial co-generation and relatively high share of refrigeration load in electricity end-use. Naturally, heating storage integrated with CHP allows decoupling of the heating demand and

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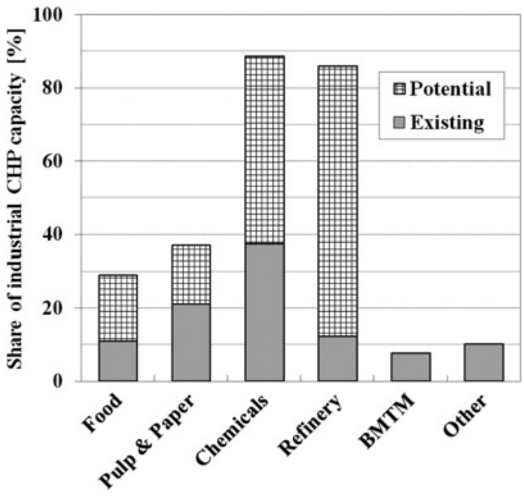

Fig. 3 *Distribution of industrial CHP capacity in the EU*

[The category 'BMTM' refers to the sub-sectors of basic metals, textiles and minerals. The estimations of CHP potential for food, paper, chemicals and refining industries from [27] are given here as a percentage of the total industrial CHP capacity for the year 2002, that is, 34.1 GW according to [26].]

supply, and therefore CHP can be run in electricity-led mode and follow DR signals, whereas cooling storage connected to electricity-based refrigeration system directly unbundles the equivalent electrical load from the main grid and creates the opportunity to control power consumption from the grid. The promising industries for RU-DR implementation based on the heating storage are all the subsectors with high CHP penetration (see Fig. 3) and in case of the cooling storage the target sub-sectors are those of food and industrial gases.

Another way of employing non-electrical storage for increasing flexibility in electricity demand is to store intermediate or end product of industrial process. From the given perspective, the industries dealing with gas compression and water desalination by reverse osmosis are found to possess a significant potential. This is explained firstly by high electricity intensity of the involved processes and secondly by the fact that certain storage capacity (gas tank, water reservoir) is normally specified by the original plant design. Support for direct use of the compressed air systems and estimation of their existing storage capacities in German industry are provided in [29]. And among the numerous studies focusing on the use of water storage in desalination plant for demand-side management one should mention [30, 31].

Combining these considerations on the three DR enabling factors, we can conclude that the overall RU-DR potential in industry is substantial and primarily concentrated within, but not limited to, the following industrial sub-sectors: food, chemicals, industrial gases, refinery/petroleum, water treatment (desalination), forest products, primary metals (iron, steel), non-metallic mineral products (cement, ceramics) and textiles.

It is important to note, however, that any realisation of the major part of the given potential requires incorporation of storage and adaptation of the industrial process control, the measures whose cost-effectiveness can be determined only by a detailed and individual investigation for each industrial customer. The remaining share of RU-DR potential, immediately available for exploitation, concerns the use of on-site mono-generation and it is already put into practice among some consumers for example, according to Pooley et al. [21] three out of nine companies, participated in the survey, use their on-site generators for enrolment in 'short-term operating reserve' programme operated by National Grid in the UK.

5 Technical efficiency of the new RU-DR scheme

Despite the presence of industries with significant potential in flexible electricity consumption, their decision to participate in the new RU-DR programme still depends on the economic incentives which in turn are highly influenced by the overall efficiency of the proposed regulation scheme. In general, the non-ideal performance of DR-based balancing mechanism, that is, incomplete utilisation of the total regulation capacity of LCFED to reduce the operating reserve needs, is explained by the factors, such as: duality of power imbalances, inaccuracy of time-step-ahead predictions and technical constraints of the consumer. In this paper, RU-DR efficiency and its dependence on the selected LCFED parameters and wind characteristics are investigated through Monte Carlo simulations in MATLAB.

5.1 Modelling assumptions

To simplify the modelling and most importantly, to unmask the effects of wind intermittency and the new RU-DR scheme, the following assumptions are adopted:

1. *Wind production*: The synthetic, 10 min wind datasets at 15 wind farm sites across New Zealand [32] are used to create normalised wind generation profiles covering period of 731 days. The wind turbine power curve is assumed cubic with nominal speed of 15 m/s. The cut-in and cut-out speed limits are ignored as they showed little impact on the results in the preliminary studies. The aggregated wind power is determined by scaling cubically the wind speeds (limited to the nominal 15 m/s) from each individual site; summing up the obtained values and then applying the normalisation. The base wind generation profile uses the datasets of all 15 wind sites and is characterised by the average value and standard deviation of $G_{av} = 0.353$ and $\sigma(G) = 0.214$, respectively (Fig. 4). The additional wind profile with the variability $\sigma(G) = 0.309$, employed in the sensitivity study, is created by grouping only three wind farms MWT1, MWT2 and MWT3 (as defined in the original data from [32]).
2. *Net load uncertainty*: Since predictability of the system demand tends to be relatively high, wind intermittency is assumed to be the only source of uncertainty. Wind power predictions G_{da} (day-ahead) and G_{tsa} (time-step-ahead) are simulated by adding to the actual wind data Gaussian noise

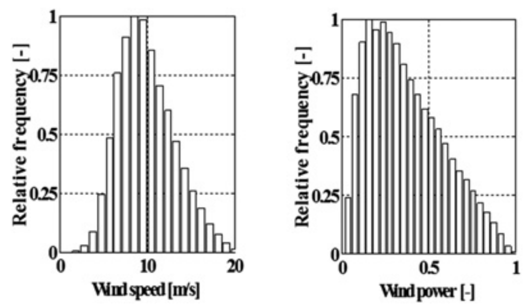

Fig. 4 *Wind speed and wind power distributions in base scenario*

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with zero mean. The chosen standard deviations of the pseudo forecast errors, that is, of the Gaussian noise, for various time horizons are shown in Table 3. The time resolution of the predicted wind profiles is reduced in accordance with the response time of LCFED by simple averaging. The wind uncertainty range is defined by 99.7% ('three sigma') confidence interval.

3. *LCFED*: Only flexible share of electricity demand of the consumers participating in RU-DR programme is considered. At the same capability for positive and negative regulations (e.g. enabled by on-site generation), this is equivalent to modelling a fully flexible consumer with the average load equal to a half of the maximum, that is, $L_{min} = 0$ and $L_{max} = 2L_{av}$. LCFED operation during the year is non-stop with the constant value of the planned daily demand $E_{L,da}$. The load ramp rates and deviations of the actual daily consumption E_L from the planned value $E_{L,da}$ are not constrained. The lead time Δt_{DR}, which also defines the control interval, is 30 min for base case scenario, although the power deviations in all simulations are calculated using the original time resolution of the wind data, that is, $\Delta t_{BAL} = 10$ min. For the purpose of comparability, the magnitude of RU-DR is set indirectly by the value of relative regulation capacity

$$\Delta L_{reg} = (L_{max} - L_{min})/\sigma(I_0) = 2L_{av}/\sigma(I_0) \quad (1)$$

where I_0 is the initial imbalance between the actual wind generation G and the day-ahead prediction G_{da}. For base configuration, the value $\Delta L_{reg} = 20\%$ is selected to represent approximately two situations: (a) initial stage of employing LCFEDs at current (low) level of wind penetration and (b) moderate application of RU-DR in future power system with very high share of renewables.

4. *Operating reserves*: The total balancing requirements for the next day are determined by the wind uncertainty range. Both up- and down-regulations are treated equally. Availability and costs of the conventional operating reserves during the day are assumed to be uniformly distributed. As a result, this permits detachment of RU-DR from the unit commitment problem and thus exclusion of the conventional generation from modelling.

5. *Power network*: The given aspect is excluded and the grid is represented simply as one node connecting the bulk wind generation and flexible load. In other words, it is assumed that spatial distribution and concentration of LCFEDs within the power system is similar to that of wind energy sources. Considering the introductory level of this study, it is actually advantageous to ignore the grid connections because otherwise it would require numerous additional assumptions related to the network, conventional load and generation that eventually would make the case scenarios too specific.

In real grid configurations, the balancing efficiency of RU-DR scheme is expected to be somewhat lower and vary

Table 3 Assumed wind forecast errors in base scenario [33]

horizon, h	0.5	1	2	13	37
$\sigma(\varepsilon)$, %	0.6	1.2	2.2	5	5.9

[Since the forecast deviation ε is assumed to be unbiased (zero mean), this allows equivalence of $\sigma(\varepsilon)$ to the original values of the normalised root-mean-square errors in [33]. The prediction errors between 13 and 37 h are obtained by linear interpolation.]

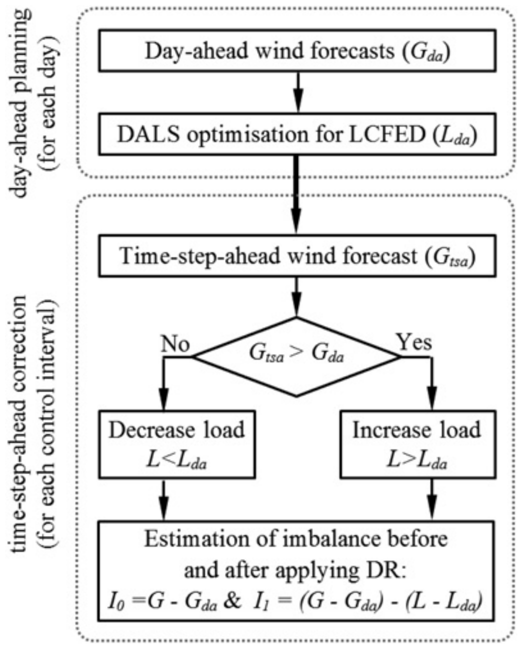

Fig. 5 *Simulation steps repeated for each operating day*

during the day, since the local power flow constraints will not allow full employment of the available regulation capacity ΔL_{reg}. In this case, however, the benefits of RU-DR can be amplified by combining it with the existing techniques for congestion management.

5.2 Simulation procedure

The resulting simulation procedure for each operating day is straightforward and as shown in Fig. 5 consists of the two major steps of the proposed RU-DR scheme: day-ahead planning and time-step-ahead correction. The challenging part within the algorithm is the DALS optimisation and it is described in detail in the following section.

The steps in Fig. 5 are performed chronologically for the selected two-year wind data. After each Monte Carlo realisation, the efficiency of RU-DR programme η_{reg} and the corresponding relative reserve reduction ΔR_{reg} are estimated based on the values of the power imbalance

$$\eta_{reg} = \frac{\sigma(I_0) - \sigma(I_1)}{L_{max} - L_{min}} \quad (2)$$

$$\Delta R_{reg} = \frac{\sigma(I_0) - \sigma(I_1)}{\sigma(I_0)} = \eta_{reg}\Delta L_{reg} \quad (3)$$

The convergence in the given Monte Carlo simulations is obtained with 100 realisations. The total calculation time when run on a workstation (Intel Xeon W3503, 12 GB random access memory, 2.4 GHz) are ~1630 and 770 s for the cases of $\Delta t_{DR} = 30$ min and $\Delta t_{DR} = 60$ min, respectively.

5.3 DALS optimisation

As it was mentioned, the optimal DALS for LCFEDs provides such distribution of their regulation capacity during the operating day that the expected residual balancing needs are minimised. Considering the adopted simplifications, this can be formulated as the following

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quadratic programming problem

$$\min \sum \left(R_{+\mathrm{res},i}{}^{2} + R_{-\mathrm{res},i}{}^{2} \right) \quad (4)$$

$$R_{+\mathrm{res},i} = G_{\mathrm{da},i} - G_{\mathrm{da,\,min},i} - R_{+\mathrm{DR},i} \quad (5a)$$

$$R_{-\mathrm{res},i} = G_{\mathrm{da,\,max},i} - G_{\mathrm{da},i} - R_{-\mathrm{DR},i} \quad (5b)$$

$$\sum L_{\mathrm{da},i} = E_{L,\mathrm{da}}; \quad L_{\min} \le L_{\mathrm{da},i} \le L_{\max} \quad (6)$$

where i is the index referring to the control time intervals during the next operating day; $G_{\mathrm{da},i}$ is the day-ahead wind power prediction; $G_{\mathrm{da,min},i}$ and $G_{\mathrm{da,max},i}$ are the boundaries of the wind uncertainty range; $L_{\mathrm{da},i}$ is the day-ahead planned loading of LCFED; $L_{\min}$ and $L_{\max}$ are the lower and upper limits in power demand; $R_{+\mathrm{DR},i}$ and $R_{-\mathrm{DR},i}$ are the potential load regulation capacities equal to $L_{\mathrm{da},i} - L_{\min}$ and $L_{\max} - L_{\mathrm{da},i}$, respectively; $R_{+\mathrm{res},i}$ and $R_{-\mathrm{res},i}$ are the residual positive and negative operating reserve needs (Fig. 6). Note that at time steps when the forecasted value of the wind power is close to nominal capacity or zero, the corresponding value of $R_{-\mathrm{res}}$ or $R_{+\mathrm{res}}$ becomes negative and therefore is excluded from the objective function (4).

The given problem is solved by using function *quadprog* from the MATLAB optimisation toolbox. Ideally, at full symmetry of the wind uncertainty range the solution consists of the flat loading profile. Since here we assume symmetric distribution of the forecast errors and uniform intraday availability of the operating reserves, the wind uncertainty range is distorted only by the physical limits of wind generation capacity, and this is when the optimised DALS is non-uniform. An example of such situation is illustrated in Fig. 6. As one can see, the predicted values of wind generation for the beginning of the day are rather low which results in higher value of the total expected demand for down-regulation compared with that for up-regulation. With the constant day-ahead dispatch plan for LCFED this irregularity of course remains, that is, $R_{-\mathrm{res},i} \gg R_{+\mathrm{res},i}$, as both the positive and negative potential balancing needs are reduced by the same amount $R_{-\mathrm{DR},i} = R_{+\mathrm{DR},i}$ (Figs. 6*a* and *c*). On the other hand, with the optimised loading schedule the regulation capacity of LCFED is redistributed to enhance its capability for down-regulation during the first 7 h of the day and thereby to smooth the variation of the residual reserve requirements (Figs. 6*b* and *c*).

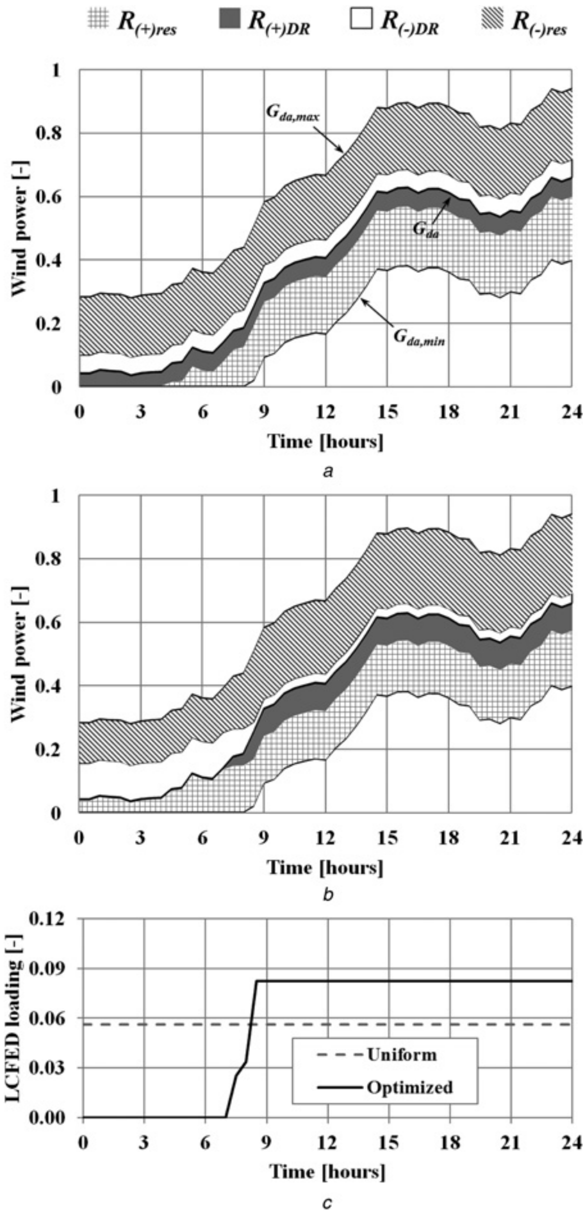

Fig. 6 *Demonstration of the effect from DALS optimisation*

a Reserve distribution for the next operating day with uniform loading schedule for LCFED
b Reserve distribution with optimised DALS
c Corresponding planned loading profiles (L_{da}) of LCFED. In this example $L_{\max} = 0.11$

5.4 Simulation results

The output of the numerical investigation is divided into three parts. The first part given in Table 4 compares the base case with the scenarios of increased wind variability and uniform loading of LCFEDs and allows the following observations:

- With RU-DR application uncertainty and variability in the wind generation are partly shifted to the consumer side. The required high flexibility in LCFED daily demand is reflected by the values $\sigma(E_{\mathrm{L}})/E_{\mathrm{L,da}} = 15$–$25\%$.
- The increased wind variability at the same level of predictability reduces RU-DR effectiveness as a result of the increased power deviations within the consumer response time when the load cannot be adjusted ($\Delta t_{\mathrm{DR}} > \Delta t_{\mathrm{BAL}}$).
- Compared with the plan with flat loading profile ($L_{\mathrm{da},i} = L_{\mathrm{av}}$), the optimised DALS allows 22% gain in ΔR_{reg} even when considering only one cause of asymmetry in the operating reserve requirements (i.e. physical limits of wind generation capacity). This means that in the real power system the benefit is expected to be higher.

The second part of the simulation results is summarised in Fig. 7 and concerns the sensitivity analysis with respect to the relative regulation capacity ΔL_{reg}, response time Δt_{DR} and uncertainty in the day-ahead wind predictions expressed by σ

Table 4 Calculation results for chosen case scenarios ($\Delta L_{\mathrm{reg}} = 20\%$)

Scenarios	$\sigma(I_0)$, %	$\sigma(E_{\mathrm{L}})/E_{\mathrm{L,da}}$, %	η_{reg}, %	ΔR_{reg}, %
base case	5.54	15.3	45.2	9.0
$\sigma(G) = 30.9\%$	6.05	24.4	39.4	7.9
$L_{\mathrm{da},i} = L_{\mathrm{av}}$	5.54	14.8	37.2	7.4

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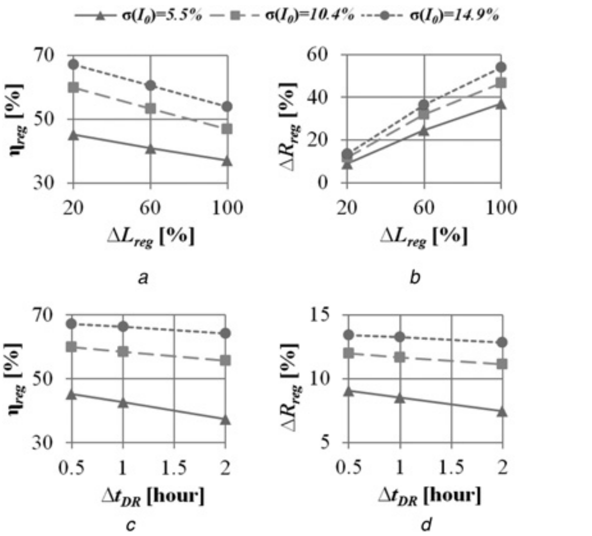

Fig. 7 *Sensitivity of RU-DR performance to selected parameters*

a Regulation efficiency versus regulation capacity
b Reduction in balancing needs versus regulation capacity
c Regulation efficiency versus response time
d Reduction in balancing needs versus response time

(I_0). The additional scenarios of $\sigma(I_0) = 10.4\%$ and $\sigma(I_0) = 14.9\%$ are obtained simply by doubling and tripling the original forecast errors in Table 3. The presented results in this case show:

- As the consumer flexibility capacity grows with respect to the level of imbalances, the regulation efficiency η_{reg} decreases (Fig. 7*a*), although of course higher reduction in the balancing needs ΔR_{reg} is achieved (Fig. 7*b*). It is explained by the fact that RU-DR can also produce over-regulation because of imperfect time-step-ahead predictions and constrained lead time ($\Delta t_{\text{DR}} > \Delta t_{\text{BAL}}$).
- The influence of the response time is moderate. The change of Δt_{DR} from 30 min to 2 h causes only 4.4–21% loss in ΔR_{reg} depending on the forecast precision (Fig. 7*d*). Thus, it should be possible to include in RU-DR the consumers with the reaction time of several hours.
- The performance of RU-DR programme improves with growing day-ahead uncertainty in the wind power. Obviously, the reason is that with the increased deviations in the day-ahead wind predictions the time-step-ahead corrections become more effective.

Finally, the third part of the calculation results is given in Fig. 8 and represents the estimations of η_{reg} and ΔR_{reg} at various levels of wind penetration and day-ahead

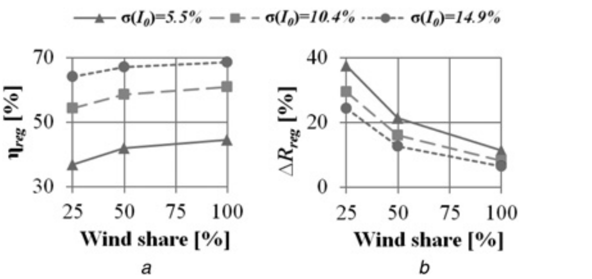

Fig. 8 *RU-DR performance at various wind penetration levels assuming LCFED share of 2% of the total demand*

a Regulation efficiency versus wind share
b Reduction in balancing needs versus wind share

uncertainty assuming the share of flexible consumption in the total electricity demand to be 2%. Such low value of LCFED load is chosen in order to demonstrate that for notable decrease in the regulation requirements by RU-DR, it is sufficient to employ a small fraction of the system demand. For example, the simulations indicate that at wind share of 25%, participation of 2% of the demand in the system balancing could reduce the reserve needs by 24–38% as shown in Fig. 8*b*. The obtained notable reduction in the balancing requirements is not surprising since 2% of the total load in this case actually provides a significant regulation capacity: $\Delta L_{\text{reg}} = 37.9$–$102.7\%$ (the relative regulation capacity can be calculated directly as: $\Delta L_{\text{reg}} = 2G_{\text{av}}[\text{LCFED share}]/\sigma(I_0)[\text{Windshare}]$)

6 Conclusions

A new RU-DR arrangement has been proposed which involves indirectly coordinated proactive dispatch of large industrial consumers aimed specifically at compensating the system imbalances caused by imprecise day-ahead wind power forecasts.

Compared with the existing RU-DR approaches based on retail RTP, balancing market and direct load control, the main respective differences of the proposed scheme are: fixed financial remuneration; centralised coordination by the BRP; and clear separation in controls of power grid and consumer facilities. As a result, the new technique guarantees availability and predictability of RU-DR; efficient utilisation of consumer flexibility in achieving the required power adjustments and, in addition, might provide economic support for the participating energy-intensive industries through discounted electricity tariffs.

The proposed RU-DR procedure is shown to be technically feasible considering: (a) high potential in self-generation and storage in industrial sector and (b) relative simplicity of the control architecture because of the absence of direct interface between BRP and consumer facilities. The suitable industries in this case are identified based on the literature review.

The performance of the alternative balancing technique and its sensitivity to the selected load and wind parameters have been evaluated by using simplified Monte Carlo simulations. The numerical results indicate that for notable reduction in the operating reserve requirements by RU-DR it is sufficient to employ only a small fraction of the system demand.

Finally, it is important to note, that this paper serves only as an introduction to the new RU-DR scheme. The detailed investigation of the proposed approach and its implementation (cost-effectiveness) in a specific country taking into account the characteristics of national power supply and industrial consumers should be the focus of future work.

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