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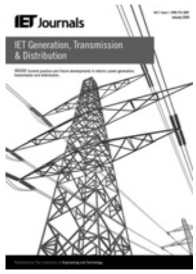

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Generation expansion planning in wind-thermal power systems

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Abstract: The intermittency and volatility of wind generation (WG) would require additional upward and downward reserves, as well as enhanced ramping capabilities in power systems. This study investigates the optimal expansion planning of fast-response generating capacity (e.g. gas-fired units) to accommodate the uncertainty of WG. The study utilises a mixed integer programming-based security-constrained unit commitment for analysing operational and reliability issues related to the proposed optimisation problem. Numerical experiments signify the effectiveness of the proposed method.

Nomenclature

The symbols used in this paper are classified into indices, parameters and variables as follows.

Indexes

t	index of planning time
i	index of thermal unit
g	index of gas-fired unit
w	index of wind generator (WG)
cm	index of compressor
s	index of scenario

Parameters and variables

PO	operation cost of generating unit
PIC	investment cost
NT	number of times under study
NI	number of thermal generation units
NG	number of gas-fired units
NW	number of WGs
NS	number of scenarios
I	unit commitment schedule vector
$F_i(\cdot)$	fuel cost function of thermal generation unit
$F_g(\cdot)$	operating cost function of gas-fired units
$F_w(\cdot)$	operating cost function of WG
P	generation dispatch of a unit
GX_g	installation status of candidate gas-fired unit g, 1 if installed, otherwise 0
wf	weighting factor (represents energy not served cost a percentage of social cost)
CENS	cost of energy not served
a, b, c	coefficients of thermal unit cost function
ga, gb, gc	gas consumption coefficients of compressor
gc	cost of natural gas contract
C_{cm}	cost of natural gas consumption of a compressor
HP	horsepower of compressor
ρ_{gas}	price of natural gas
f_{gas}	natural gas consumption of gas-fired unit
LS	amount of scheduled load shedding
EENS	expected energy not served
VOLL	value of lost load
PR(Z_s)	individual probability of forced outage of Z_s (MW)
Z_s	load shedding in the sth contingency scenario
EC_s	energy curtailed due to forced outage of Z_s MW
D	power system demand
GL	total generation capacity of power system
USR, DSR	system up/down spinning reserve requirement without the WG uncertainty

ASR_U, ASR_D	coefficients of up/down spinning reserve due to the WG uncertainty
US_{it}, DS_{it}	up/down spinning reserve of unit i at time t
RU_i, RD_i	ramp up/down limit of unit i
$d\%$	percentage of unit capacity available for reserve
MSR	maximum sustained ramp rate (MW/min)
X_{it}^{on}, X_{it}^{off}	period that unit i has been on/off at time t
T_i^{on}, T_i^{off}	minimum up/down time of unit i
κ, η	Weibull's probability distribution function shape and scale parameter
v, v_{CI}, v_{CO}, v_R	instantaneous, cut-in, cut-out and rated wind speed
P_w^*	available WG power
PW	system's total WG
SRC	system total ramping capability
SRCD	system ramp down capability without gas-fired unit contribution
SRCU	system ramp up capability without gas-fired unit contribution

1 Introduction

Wind generation (WG) emerges with new challenges in power systems. In practice, WG large forecasting errors are not uncommon [1, 2]. Therefore the volatile nature of WG would require a more sophisticated approach to the planning and operation of power systems [3, 4]. During the last decade, the capital cost of WG has substantially decreased, which has made WG a serious contender among generation resources [5, 6]. The environmental concerns have also persuaded governments to impose additional restrictions such as production tax credit (PTC) on carbon production and enhanced standards and initiatives such as renewable portfolio standard (RPS) and regional greenhouse gas initiative (RGGI) for expanding renewable energy generation [7].

The intermittent nature of WG would create a planning challenge for calculating the optimal size of reserve and generation ramping that could guarantee a reliable supply of load. The WG penetration could result in power system vulnerabilities, if ancillary services are not scheduled properly [3, 4]. The additional reserves must also be co-ordinated with ramping requirements in order to respond to WG interruptions quickly. Temporary solutions like the utilisation of storage systems or additional power exchanges with adjacent power systems have been considered. However, the most effective solution for responding to the volatility and intermittency of WG is the use of fast-response conventional generation systems for compensating the WG shortcomings [8].

Several publications have addressed the WG integration in power systems. The impact of large-scale WG on the scheduling of conventional generation is investigated when considering the operation cost and reliability of the system [8]. The impact of wind forecasting errors on power system operations is discussed in [1] by applying different unit commitment models. In [9] by applying the Monte-Carlo simulation, a security-constrained unit commitment algorithm has been developed that takes into account the intermittency and variability of wind power generation. An economic dispatch model was developed in [10] by applying genetic algorithm. The incorporation of wind energy conversion system in power system unit commitment and economic dispatch was discussed in [11]. A co-ordinated wind-thermal dispatch using direct search method was presented in [12]. A combination of branch and bound and dynamic programming algorithms was developed in [13] to model the co-ordinated economic dispatch of wind and thermal generation in isolated power systems. The impact of transmission capacity on the WG expansion was discussed in [14], which considered additional zonal reserves for an uncertain WG. The adequacy of power systems with WG was evaluated in [15]. A few articles investigated the utilisation of demand response for the reliability enhancement when considering the WG uncertainty [16–18]. The main problem with such approaches is that the amount of interruptible load is usually small as compared with drastic WG changes. However, very few articles considered power system operation issues in the WG expansion planning.

This paper presents a co-ordinated wind-thermal planning framework for managing hourly WG operation issues. We utilise fast-response generating units to respond to the unpredictability of WG. The quick-start and high ramping capability of fast-response generating units allows units to reach a maximum capacity in a short time. This is a NP-complete non-convex large-scale mixed-integer optimisation problem [19]. A mixed-integer linear programming (MILP) algorithm is utilised which presents attractive features, including short convergence time, simplicity of algorithm, linearity of constraints and ability to handle large-scale problems. In our proposed stochastic resource planning problem, each possible system state is represented by a scenario. The consideration of power system component outages and the WG volatility along with the load forecast uncertainty could results in a large number of scenarios. The number of scenarios would have a substantial impact on computational requirements. So, we determine a subset of scenarios and a probability measure based on this subset that is the closest to the initial probability distribution in terms of probability metrics.

The rest of this paper is organised as follows. Section 2 briefly introduces mathematical model of wind generators. Section 3 presents problem formulation and the objective function. Incorporation of WG in optimal scheduling model with the prevailing constraints is provided in Section 4. Stochastic planning is discussed in Section 5. Section 6 presents a numerical experiments and results. Lastly, in Section 7, the conclusions drawn from the studies are provided.

2 Mathematical model of wind generators

The wind speed distribution is modelled by the Weibull probability distribution function (PDF) [20–22] as

$$f(v) = \frac{\kappa}{\lambda}\left(\frac{v}{\lambda}\right)^{\kappa-1} \cdot \exp\left[-\left(\frac{v}{\lambda}\right)^{k}\right] \quad (\kappa > 0, v > 0, \lambda > 0) \quad (1)$$

We assume the WG volatility is subject to a Weibull PDF, that is, $f(v)$, where k is the shape factor based on historical data and λ is the scale factor which represents the forecasted WG.

Various methods for estimating Weibull's parameters are discussed in [23–25]. The power output of a wind turbine [26, 27] is given as

$$P^{*}_{\rm wt} = \begin{cases} P^{\max}_{\rm w} \dfrac{v^{\kappa} - v^{\kappa}_{\rm CI}}{v^{\kappa}_{R} - v^{\kappa}_{\rm CI}} & (v_{\rm CI} \le v \le v_{\rm R}) \\ P^{\max}_{\rm w} & (v_{\rm R} \le v \le v_{\rm CO}) \\ 0 & (v < v_{\rm CI} \text{ and } v > v_{\rm CO}) \end{cases} \quad (2)$$

There is a small cost associated with WG operations. The market price of WG is determined based on bilateral contracts or locational marginal prices. Upper and lower WG are constrained by the physical characteristics of WG units as well as the optimal operation of power systems.

3 Mathematical formulation

The power system's objective (3) is to minimise the social cost (operating cost of existing generation units plus investment costs of new gas-fired units for catering to WG uncertainty). This objective is subject to unit and system constraints, including new unit installation status and commitment states (6) and (7), thermal and gas-fired unit cost function (8) and (9), fuel and compressor costs in gas-fired units (10) and (11), contingency condition (12)–(16), system constraints (17)–(19), generating unit physical constraints (20)–(29), WG constraints (30)–(33) and system ramping capability (34)–(36). The planned WG capacity is assumed to be known based on a given criterion such as the RPS plan.

3.1 Objective function

$$\text{Min PO} + \text{PIC} \quad (3)$$

such that

$$\text{PO} = \sum_{s=1}^{\rm NS}\sum_{t=1}^{\rm NT}\left\{\sum_{i=1}^{\rm NI}[F_i(P_{its})I_{its}] + \sum_{g=1}^{\rm NG}[F_g(P_{gts})I_{gts}] + \sum_{w=1}^{\rm NW}[F_w(P_{wts})] + \text{wf} \times \text{CENS}_{ts}\right\} \quad (4)$$

$$\text{PIC} = \sum_{g=1}^{\rm NG} IC_g P_{\max,g} GX_{gt} \quad (5)$$

$$GX_{g(t-1)} \le GX_{gt} \quad (6)$$

$$I_{gts} \le GX_{gt} \quad (7)$$

$$F_i(P_{it}) = a_i + b_i P_{its} + c_i P^2_{its} \quad (8)$$

$$F_g(P_{gts}) = gc_{ts} + C_{{\rm cm},ts} \quad (9)$$

$$gc_{ts} = \rho_{{\rm gas},t} f_{{\rm gas},gts} \quad (10)$$

$$C_{{\rm cm},ts} = ga + gb\text{HP}_{{\rm cm},s} + gc\text{HP}^2_{{\rm cm},s} \quad (11)$$

$$\text{CENS}_{ts} = \text{EENS}_{ts} \times \text{VOLL} \quad (12)$$

$$\text{EENS}_t \le \text{EENS}^{\max} \quad (13)$$

$$\text{EENS}_t = \sum_s (\text{PR}(Z_{ts})\text{EC}_{ts}) \quad (14)$$

$$\text{EC}_{ts} = \begin{cases} D_t - (GL_{ts} - Z_{ts}), & \text{when } D_{ts} > GL_{ts} - Z_{ts} \\ 0, & \text{otherwise} \end{cases} \quad (15)$$

$$\text{GL}_{ts} = \sum_{i=1}^{\rm NI} P^{\max}_{its} + \sum_{g=1}^{\rm NG} P^{\max}_{gts} + \sum_{w=1}^{\rm NW} P^{\max}_{wts} \quad (16)$$

3.2 Power system constraints ($\forall t = 1, \ldots, DT$)

3.2.1 Power balance constraint

$$\sum_{i=1}^{\rm NI} P_{its}I_{its} + \sum_{g=1}^{\rm NG} P_{gts}I_{gts} + \sum_{w=1}^{\rm NW} P_{wts} = D_{ts} \quad (17)$$

Load shedding could be considered in the case of contingencies.

3.2.2 System up/down spinning reserve requirements:

$$\sum_{i=1}^{\rm NI} \text{US}_{its} I_{its} + \sum_{g=1}^{\rm NG} \text{US}_{gts} GX_{gt} \ge \text{USR}_t + \text{ASR}_U\left(\sum_{w=1}^{\rm NW} P_{wts}\right) \quad (18)$$

$$\sum_{i=1}^{\rm NI} \text{DS}_{its} I_{its} + \sum_{g=1}^{\rm NG} \text{DS}_{gts} I_{gts} \ge \text{DSR}_t + \text{ASR}_D\left(\sum_{w=1}^{\rm NW} P^{\max}_{w} - \sum_{w=1}^{\rm NW} P_{wts}\right) \quad (19)$$

Equations (18) and (19) indicate that the system would require hourly up/down spinning reserves for responding to WG uncertainties. Extra reserve requirements are in proportion

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to estimated hourly WGs, which are represented by ASR_U and ASR_D factors. Fast-response gas-fired generation units can enhance the system's up/down reserve requirements as discussed here. Theoretically, if the number of scenarios be large enough, then the reserve requirement can be neglected, that is, the reserve parameters (USR, DSR, ASR_U and ASR_D) would take smaller values. However, in practice there is always a trade-off between accuracy and speed. Therefore here we considered a combination of scenario-based and regulatory reserve constrained models.

3.3 Thermal and gas-fired generating unit constraints

3.3.1 Generation capacity limit

$$P_i^{\min} I_{its} \le P_{its} \le P_i^{\max} I_{its} \tag{20}$$

$$0 \le P_{gts} \le P_g^{\max} I_{gts} \tag{21}$$

3.3.2 Up/down 10-min spinning reserve contribution

$$\mathrm{US}_{its} = \mathrm{Min}\{d\% \times P_i^{\max}, 10 \times \mathrm{MSR}_i, P_i^{\max} - P_{its}\} \tag{22}$$

$$\mathrm{DS}_{its} = \mathrm{Min}\{d\% \times P_i^{\max}, 10 \times \mathrm{MSR}_i, P_{its} - P_i^{\min}\} \tag{23}$$

3.3.3 Ramping up/down constraints

$$P_{its} - P_{i(t-1)s} \le [1 - I_{its} \times (1 - I_{i(t-1)s})]\mathrm{RU}_{its} + I_{its}(1 - I_{i(t-1)s})P_i^{\min} \tag{24}$$

In (24) and (26), the assumption is that the thermal units can start-up/shutdown only at their minimum generation limit.

$$\mathrm{RU}_{its} = \mathrm{Min}\{\mathrm{RU}_i, P_i^{\max} - P_{its}\} \tag{25}$$

$$P_{i(t-1)s} - P_{its} \le [1 - I_{i(t-1)s} \times (1 - I_{its})]\mathrm{RD}_{its} + I_{i(t-1)s}(1 - I_{its})P_i^{\min} \tag{26}$$

$$\mathrm{RD}_{its} = \mathrm{Min}\{\mathrm{RD}_i, P_{its} - P_i^{\min}\} \tag{27}$$

3.3.4 Minimum up/down time constraints

$$(X_{i(t-1)s}^{\mathrm{on}} - T_i^{\mathrm{on}}) \times (I_{i(t-1)s} - I_{its}) \ge 0 \tag{28}$$

$$(X_{i(t-1)s}^{\mathrm{off}} - T_i^{\mathrm{off}}) \times (I_{its} - I_{i(t-1)s}) \ge 0 \tag{29}$$

4 Wind generator constraints

WGs incur additional constraints to optimal scheduling problem. Three constraints could limit the available WG as follows:

1. Wind velocity (2)

2. System spinning reserve (32)

3. System maximum ramping capability (33)

$$0 \le P_{wts} \le P_{wts}^{*} \tag{30}$$

$$\mathrm{PW}_{ts} = \sum_{w=1}^{\mathrm{NW}} P_{wts} \tag{31}$$

Using (18) and (31), the system up-spinning reserve limit is linked with the maximum available WG as

$$\mathrm{PW}_{ts} \le \frac{\sum_{i=1}^{\mathrm{NI}} (\mathrm{US}_{its} I_{its}) + \sum_{g=1}^{\mathrm{NG}} \mathrm{US}_{gts} GX_{gt} - \mathrm{USR}_t}{\mathrm{ASR_U}} \tag{32}$$

The hourly system ramping capability is linked to the hourly change in the WG output as

$$|\mathrm{PW}_{ts} - \mathrm{PW}_{(t-1)s}| \le \mathrm{SRC}_{ts} \tag{33}$$

where (see (34))

and

$$\mathrm{SRCD}_{ts} = \sum_{i=1}^{\mathrm{NI}} [\mathrm{Min}(60 \times \mathrm{RD}_i, P_{i(t-1)s} - P_i^{\min})] \tag{35}$$

$$\mathrm{SRCU}_{ts} = \sum_{i=1}^{\mathrm{NI}} [\mathrm{Min}(60 \times \mathrm{RU}_i, P_i^{\max} - P_{i(t-1)s})] \tag{36}$$

Here ΣP_{gs} is the total planning candidate gas-fired generation. GX_{gt} is the decision variable for the required gas-fired generation to compensate WG deficiencies. Equation (35) forms a non-linear constraint. Therefore to keep the problem in linear conditions, this constraint is linearised by using auxiliary binary variables discussed in Section 10.1 (Appendix). The problem in (4)–(36) in addition to DC network security constraints provided in [28] is solved at all scenarios as explained in the following section.

$$\mathrm{SRC}_{ts} = \begin{cases} \mathrm{SRC}_{ts} + \sum_{g=1}^{\mathrm{NG}} P_{gs} GX_{gt}, & \text{if } \mathrm{PW}_{ts} \ge \mathrm{PW}_{(t-1)s} \\ \mathrm{SRCU}_{ts} + \sum_{g=1}^{\mathrm{NG}} (P_g^{\max} - P_{gts}) GX_{gt}, & \text{if } \mathrm{PW}_{ts} \le \mathrm{PW}_{(t-1)s} \end{cases} \tag{34}$$

5 Stochastic planning solution

The Monte-Carlo simulation along with a scenario reduction technique is applied to generate scenarios that simulate random characteristics of system components. The stochastic model is proposed which considers outages of generator and transmission system components as well as the uncertainty of load and available wind forecasts in the proposed scenarios. A set of possible scenarios is considered for modelling the uncertainties in the long-term planning problem. We assign a weight, PRs, to each scenario that would reflect the probability of the occurrence of the scenario. The WG planning would form a large-scale problem when considering operating constraints. Hence the Monte-Carlo simulation method is well-suited for such an application because the number of samples for a given accuracy level is independent of system size. A detailed formulation of Monte-Carlo approach for creating scenarios in power system operation with uncertainties can be found in [29, 30].

To address the volatility of WG, we assume the wind power is subject to a Weibull distribution, that is, $W(k, \lambda)$ where k is the shape factor achieved from historical data and λ is the scale factor which represents the forecasted WG. The Monte-Carlo simulation will generate a large number of scenarios subject to a Weibull distribution. A probability is assigned to each scenario, that is, one divided by the number of generated scenarios. In each scenario, an hourly random wind power generation is considered which is based on the forecasted wind power generation.

The simulation of power system component outages, volatility of WG and uncertainty of load forecast would result in a large number of scenarios. On the other hand, the large number of scenarios would have a substantial impact on the computational requirements of the scenario-based optimisation model. Therefore using an effective scenario reduction method would be very essential for large-scale systems [29]. The reduction technique would present a scenario-based approximation with a smaller number of scenarios for a reasonably good representation of the original system. So, we determine a subset of scenarios and a probability measure based on the subset that is the closest to the initial probability distribution in terms of probability metrics. A general algebraic modelling system (GAMS) is used in this study. GAMS provides a tool called SCENRED for scenario reduction. The scenario reduction algorithm provided by SCENRED determines a scenario subset (of prescribed cardinality or accuracy) and assigns optimal probabilities to the preserved scenarios [31].

6 Numerical results

In this section, two case studies are presented. In Section 6.1, different aspects of centralised and distributed expansion of WG are discussed. The purpose is to investigate the planning of fast-response gas-fired generation units to compensate WG uncertainties. In this paper, we assumed that market participants (e.g. GENCOs) already expressed their willingness to install new generation units by submitting the proposals to the ISO. Therefore ISO's role is to accept the proposals which benefit the system the most. In Section 6.2, a six-bus test system is selected to investigate the effect of network constraints on the proposed hybrid expansion planning. The spinning reserve parameters are $ASR_U = 20\%$, $ASR_D = 50\%$, wf = 1 and VOLL = 1000 \$/MWh. The WG parameters are $v_{CI} = 5$, $v_R = 15$ and $v_{CO} = 45$ m/s and the Weibull wind speed PDF is assumed to have $k = 2$ and $\lambda = 20$. Wind farms are assumed to operate with a negligible cost. In the following numerical experiments, the effect of gas transmission network is not considered. However, when the penetration of gas-fired units increases in the system, the impact of gas transmission network could be significant. This is the subject of our future research. The problem is coded in the GAMS with CPLEX 11.0 solver on a 2.4 GHz server computer with 64 GB memory.

6.1 Centralised and distributed wind models

The study period is one year with hourly simulations. The base-case load profile and the system data are given in Section 10.2 (Appendix). USR is assumed to be 10% of the load. The computation time for the scenario-based problem depends on the number of scenarios. The scenario reduction method would reduce the total number of scenarios from 100 to 10 as a trade-off between the solution speed and accuracy. Table 1 shows the weights of each scenario after reduction. The WG in power systems is simulated in four possible modes as follows.

6.1.1 Centralised planning: *Wind unit only planning:*

WG expansion is concentrated in a limited area. The WG intermittency could result in higher load shedding if system reserves/ramping cannot accommodate large changes in WG. The other shortcoming of centralised investment could be the lack of large access to transmission capacity [32], which is beyond the scope of this discussion. Table 2 shows the simulation results for three different wind patterns in the zone without the addition of any gas-fired units. In this case, the installed wind capacity is 90 MW and the total thermal generation is 525 MW.

Table 1 Weight of each scenario after scenario reduction

Scenario	1	2	3	4	5	6	7	8	9	10
Weight, %	5.1	0.1	0.1	0.1	61.2	4.1	6.9	0.1	4.8	17.5

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Table 2 Centralised WG without gas-fired generation expansion

Capacity factor, %	Social cost, M$/year	
	With load shedding	Without load shedding
39	46.81	infeasible
45	45.85	infeasible
55	44.4	44.4

The capacity factor of a WG is the ratio of the actual power generation over a given period to its output if it had operated at full nameplate capacity the entire time. In Table 2, when the WG capacity factor is not large enough the solution is infeasible because the gas-fired generation capacity is not increased accordingly. This is because the existing generation units cannot provide the required spinning reserve or the system ramping capability is not sufficient to accommodate the WG fluctuations. However, a higher WG capacity factor would offer a more robust power system. If the load shedding is allowed, a feasible solution is possible at higher operating costs.

Combined wind and gas-fired unit planning: To maintain a secure operation, the combined wind-thermal planning is investigated in a centralised case. The capacity factor of WG is 39%. In this case, there is an option of installing new gas-fired units to prevent emergency load shedding. One of the major challenges would be determining the optimal reserve and its associated gas-fired unit capacity. Fast-response units provide large ramping rates which enhance the SRC along with the available 10-min spinning reserve. On the other hand, the cost of these units is usually high (e.g. annualised investment cost of $100 k/MW is assumed). The stochastic solution provides a total objective value of $51.95 M/year. The social cost is higher than that of the previous case when the cost of gas-fired capacity expansion is considered. However, this extra cost would benefit the social welfare by not enforcing the service curtailment to the consumers. The gas-fired unit is installed on 24th June, which is the beginning of hot season with higher hourly demands. Furthermore, the WG output would experience more fluctuations in the summer months, that is, wind speed is smaller and there would be high possibility that the WG output falls to zero ($v < v_{CI}$).

6.1.2 Dispersed planning:

Wind unit only planning: WG farms located in a limited geographical area could increase the risk of power shortages at certain periods when the wind is not available. On the other hand, WG farms dispersed at several zones may impose additional financial risks if some of those locations possess a low quality wind. In such cases, local authorities may provide additional incentives to investors, such as easier transmission access or faster grid connection time, to encourage the dispersion of wind farms. Indeed, the diverged planning option would result in higher system reliability if the wind is more readily available at individual zones. Assume that there are three wind farms in separate zones, each with a capacity of 30 MW (total wind capacity is the same as that in the centralised case, see Section 6.1.1) and WG capacity factor in the two remote zones are 37 and 36% which are less than that in the local site (39%).

Fig. 1 depicts the average WG variation in a 24-hour period of the operation in aforementioned three zones. Comparing with the case in Section 6.1.1 (Wind unit only planning), someone would learn that wind shortages in one zone could be covered by those in other zones (e.g. in Fig. 1 wind speed is low at hour 11 in zone 1, whereas it is higher in zones 2 and 3). Therefore the probability of large WG deficits is reduced. The study results show that the social cost is $47.06 M/year and no gas-fired capacity expansion is needed. Despite the fact that the total capacity factor in remote zones are less than 39% (as was in the centralised zone), the cost decreases as compared to that in the centralised case. Therefore not only the WG capacity factor is an important factor in locating new wind farms, but also distance to the existing ones can significantly affect system reliability.

In another study, the available generation capacity is on outage by 20% and load shedding is considered at the cost of 1000 $/MWh. Here, the available thermal and WG capacity is higher than the peak-load of 503.42 MW and the social cost is $117.14M. This is because the available WG is significantly less than its rated value in most periods. The fast-response gas-fired generation is considered next.

Combined wind and gas-fired unit planning: As discussed in Section 6.1.2 (Wind unit only planning), when WG farms are dispersed geographically, the optimal solution may not require any gas-fired capacity expansions. However, the expansion of fast-response gas-fired units will provide spinning reserves and ramping requirements when considering the existing thermal unit outages. Table 3 shows the results of existing generation capacity outages. In Table 3, the larger rate of capacity outage would result

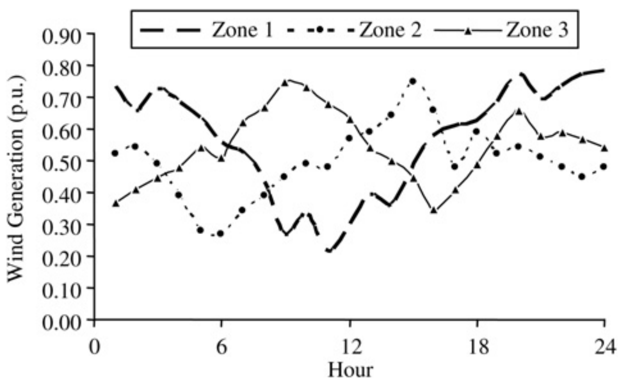

Figure 1 *24-hour average WG in three zones*

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Table 3 Changes in social costs when resources are on outage

Capacity outage	Gas-fired installation period, hours/month	Social cost, M$
thermal by 20%	212/January	57.35
thermal by 10%	4096/May	52.66
thermal by 5%	4910/July	51.69

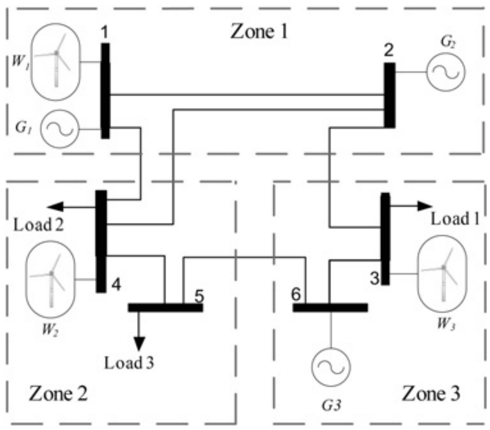

Figure 2 *Six-bus system single diagram*

Table 4 WGs expansion plan in six-bus test case system

Bus number	WG capacity, MW	Grid connection time, year	Wind zone	Wind zone capacity factor, %
1	80	1	1	45
4	60	3	2	40
3	40	5	3	35

in the earlier generation capacity expansion as well as higher social costs.

The wind speed pattern has a substantial impact on fast-response generation expansion. The generation capacity expansion needs to be enhanced when the WG capacity factor is less than expectation. If we decrease the capacity factor in the three zones to 30, 28 and 27%, respectively, generation expansion will occur at hour 4913 while the social cost increase to $53.05M.

Table 6 Weights of each scenario after scenario reduction

Scenario	1	2	3	4	5	6
Weight	0.05	0.08	0.23	0.04	0.06	0.24
Scenario	7	8	9	10	11	12
Weight	0.05	0.045	0.045	0.015	0.045	0.1

6.2 Six-bus test case

This case demonstrates the effectiveness of the proposed approach for solving the optimal planning problem in a transmission-constrained power system. The optimal capacity of gas-fired generation units associated with the WG uncertainty is investigated. In addition, the impact of WG expansion on power system operation is studied. The system is shown in Fig. 2 [33] and the system data are provided in Section 10.3 (Appendix). The planning period is five years and WGs come into service at the beginning of each planning year according to the plan given in Table 4. The maximum load is 505 MW and the average load is 300 MW in the initial year of study, which is increased 5% annually in the base-case scenario. The candidate gas-fired generating units are given in Table 5. The scenario weights after reduction are shown in Table 6.

6.2.1 Fast-response generating units requirement: Table 7 summarises the generating unit installation schedule in the planning period. The earliest installed fast-response unit is unit 4. This unit shows a balance of investment and operating costs. Furthermore, this generation unit is located at load bus 4 where WG 2 is installed in year 4. However, with an increase in WG penetration and transmission capacity limitations, extra fast-response units are installed in the last planning year. The candidate generation unit 6 is installed at bus 6

Table 5 Candidate fast-response gas-fired generation units

Bus number	Capacity, MW	Investment cost, k$/MW/year	Operating cost, k$/MWh	MSR, MW/min	Ramp up/down, MW/h	*d*%
1	50	65	15	8	100	80
2	50	60	18	8	100	80
3	50	55	18	8	100	80
4	50	50	21	8	100	80
5	50	45	23	8	100	80
6	50	40	24	8	100	80

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Table 7 Generating units installation time

Unit	1	2	3	4	5	6
Hour (year/month)	40 357 (5/August)	—	39 974 (5/July)	31 213 (4/July)	–	39 973 (5/July)

in the summer of year 5. At the same time, candidate unit 3 is added to the load bus 3. In addition, candidate unit 1 is installed at bus 1 where the largest WG is located. The major reason for adding this gas-fired unit at a later period, while it has the lowest operating cost, is that the bus 1 in zone 1 has a favourable wind speed, which would reduce the necessity of adding fast-response unit.

6.2.2 Sensitivity analysis of spinning reserve and social cost: In Table 7, the fast-response units are installed to compensate the WG uncertainty which would increase the required spinning reserve capacity. The experiments demonstrate changes in system parameters as a result of WG capacity expansion. Fig. 3 depicts variations in average up/down spinning reserve requirements when WG penetration increases. Here the base case (Section 6.2.1) represents zero percent wind capacity increase. ASR_D is assumed to be larger than ASR_U, so the down spinning reserve is more influenced by the WG penetration. Hence, the down spinning reserve variation curve has a larger gradient as compared to that of the up-spinning reserve.

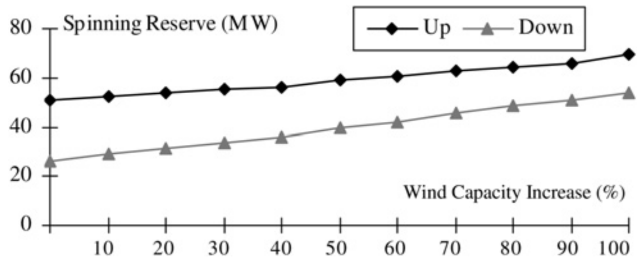

Figure 3 *Average Up/down spinning reserve by increasing the WG capacity*

Increase in WG penetration would change reserve requirements and consequently affects generation scheduling. Different approaches used in literatures aimed to obtain optimal reserve requirements [34–36]. However, determining optimal amount of reserve requirements which consider security and economy of the system is still an open question. This deserves to be the subject of a separate paper, especially when there is large wind power penetration in the system. Based on the proposed approach, the amount of reserve requirement is directly influenced by ASR_U and ASR_D parameters. Therefore finding optimal values of these parameters would be essential. Fig. 4 depicts variation of the production, energy not served (ENS) and total operating (OP) costs when reserve parameter change. As the study shows, the minimum operating cost is obtained when $ASR_U = 1.1$ (i.e. roughly 5.5 times the wind to thermal installed capacity ratio). In the similar study, minimum OP is obtained when $ASR_D = 2$ (i.e. roughly 10 times the wind to thermal installed capacity ratio). However, the value of these parameters may change in different systems and with various wind speed pattern.

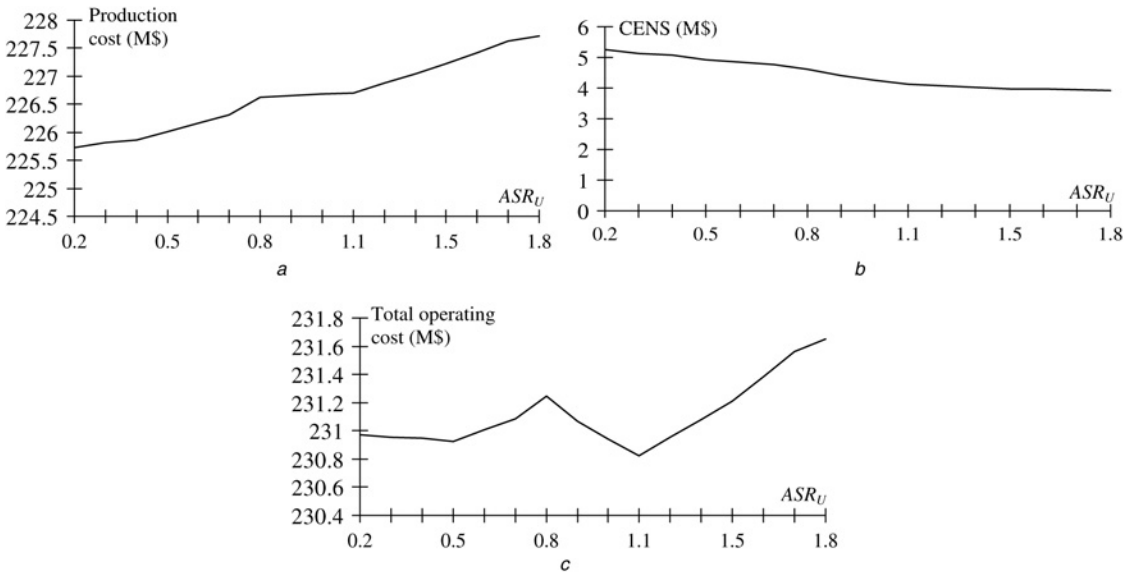

Figure 4 *The effect of the variation of reserve parameter on system costs*

a Production
b ENS
c Total operation costs variation for change of ASR_U

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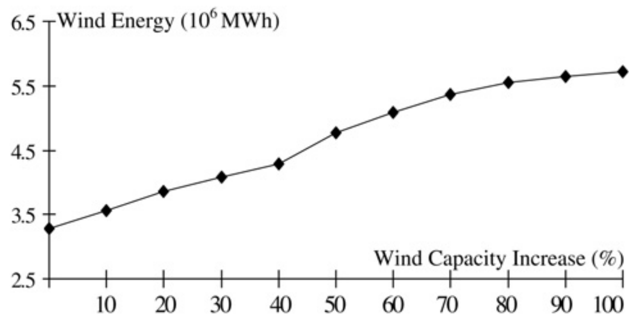

Figure 5 *WG variation by increasing the WG capacity*

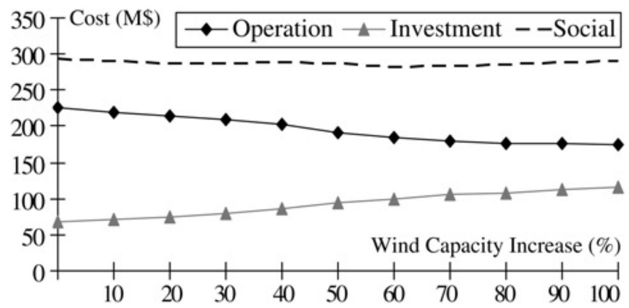

Figure 6 *Cost variations by increasing the WG capacity*

Fig. 5 shows the WG (MWh) addition as a result of the WG capacity (MW) expansion. However, the WG gradient decreases gradually since the system reserve and ramping capability would constrain WG. On the other hand, system may not have the capability (reserve, ramping etc.) of absorbing the whole available WG when the wind penetration is significant. Hence, fast-response units are installed when WG capacity increases by 40%. However, WG cannot increase further when the WG capacity is increased beyond 80% which is due to transmission constraints.

In Fig. 6, operation costs decrease by increasing the WG capacity. On the other hand, fast-response units are installed at additional costs to compensate the WG uncertainty. Therefore the optimal social cost provides planners with a trade-off for the optimal WG capacity expansion. In this case, the minimum social cost is $282.72M which is achieved when the WG capacity increases by 60%.

7 Conclusions

A stochastic model for long-term generation scheduling problem is proposed in this paper. Scenario-based approach along with modified reserve and ramping constraints are modelled considering trade-off between accuracy and calculation time. Fast-response generating unit expansion is considered to alleviate WG uncertainty impacts on system reliability.

In many countries, the expansion planning of renewable energy resources is usually based on pre-scheduled or regulatory plans. We assume the WG expansion plan is given, and utilise gas-fired units as candidates to cater to the volatility and intermittency of WGs. The proposed long-term scheduling considers operating issues (e.g. system reserves and ramping of thermal units) for enhancing the system reliability. The fast-response units are costly and may contribute to emission. The optimal size and type of these units are determined in the proposed approach. Case studies showed the effectiveness of the proposed model and the effects of system component outages and load and WG uncertainties on generation capacity expansion plans and costs. Numerical experiments showed that fast-response units can improve the reliability of power systems with a large penetration of volatile WG, especially in the limited geographical area. The size of the problem becomes too large when considering detailed operation constraints, and the calculation time would increase. In such cases, proper simplifications, for example, decomposition methods or parallel simulation can be utilised for large system solutions.

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10 Appendix

10.1 Linearising non-linear constraint using auxiliary binary variables

Equation (34) represents a non-linear conditional constraint which is modelled in MILP by using an auxiliary integer variable approach presented in Table 8. Table 8 shows that (34) conditional non-linear constraints can be modelled by linear constraints as follows

$$\mathrm{PW}_t - \mathrm{PW}_{t-1} \le (m-\varepsilon)\delta + \varepsilon \tag{37}$$

$$\mathrm{SCR}_t - \mathrm{SRCU}_t - \sum_{g=1}^{\mathrm{NG}} (P_g^{\max} - P_{gt}) \le M(1-\delta) \tag{38}$$

$$\mathrm{SCR}_t - \mathrm{SRCU}_t - \sum_{g=1}^{\mathrm{NG}} (P_g^{\max} - P_{gt}) \ge m(1-\delta) \tag{39}$$

Table 8 MILP representation of conditions

#	Condition	Represented by
1	$\sum_j a_j x_j \le b \rightarrow \delta = 1$	$\sum a_j x_j - (m-\varepsilon)\delta \ge b + \varepsilon$
2	$\delta = 1 \rightarrow \sum_j a_j x_j = b$	$\sum a_j x_j + M\delta \le M + b$
		$\sum a_j x_j + m\delta \ge m + b$
3	$\sum_j a_j x_j \ge b \rightarrow \delta = 0$	$\sum a_j x_j + (M+\varepsilon)\delta \le M + b$
4	$\delta = 0 \rightarrow \sum_j a_j x_j = b$	$\sum a_j x_j - M\delta \le b$
		$\sum a_j x_j - m\delta \ge b$

Table 10 Load profile

Months	Total, GWh	Average, MW	Peak, MW
January	239.45	321.42	413.74
February	209.82	312.23	403.81
March	223.62	300.56	388.47
April	196.62	273.09	351.59
May	204.82	275.29	394.36
June	226.82	315.02	466.41
July	228.14	306.63	499.66
August	249.26	335.02	503.42
September	208.97	292.11	429.61
October	208.16	279.78	359.77
November	203.43	283.05	377.92
December	222.98	299.70	414.55

Table 11 Six-bus system generation data

Bus number	Capacity, MW	Ramp up/down, MW/h	MSR, MW/min	*d*%	FOR, %
1	180	60	2	50	5
2	130	60	2	50	5
6	100	60	2	50	5

Table 12 Six-bus system transmission data

Line number	From bus	To bus	Reactance, Ω	Capacity, MW
1	1	2	0.17	130
2	2	3	0.037	120
3	1	4	0.258	170
4	2	4	0.197	140
5	4	5	0.037	100
6	5	6	0.14	170
7	3	6	0.018	160

Table 9 Generation data

Unit type	Capacity, MW	Ramp-up/down, MW/h	MSR, MW/min	*d*%	Levelised investment cost, k$/MW/year	FOR, %
thermal	525	180	6	50	existing unit	5
gas	100	300	10	40	100	5
wind	90	90	0	0	existing unit	0

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$$PW_t - PW_{t-1} \leq M - (m + \varepsilon)\delta \quad (40)$$

$$SCR_t - SRCD_t - \sum_{g=1}^{NG} P_{gt} \leq M\delta \quad (41)$$

$$SCR_t - SRCD_t - \sum_{g=1}^{NG} P_{gt} \geq m\delta \quad (42)$$

where M is an upper bound and m is a lower bound for the expression $(\Sigma_j a_j x_j - b)$ and ε is a small tolerance value.

10.2. Data for centralised and distributed cases

Generation data and load profile are given in Tables 9 and 10.

10.3 Six-bus system data

Six-bus system data are given in Tables 11 and 12.