Assessment of the Role and Value of Frequency Response Support from Wind Plants

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***Abstract* — High penetration of wind generation causes concerns over frequency stability, as currently wind plants do not provide frequency response support. Extensive research has been conducted to investigate alternative designs of controllers to facilitate the provision of synthetic inertia and primary frequency response from wind plants. However, frequency response support from wind plants differs from that provided by conventional plants and its impact on the system's economic performance is not yet fully understood. In this context, this paper develops a novel methodology to incorporate the frequency response support from wind plants into generation scheduling, thus enabling the benefits of alternative control strategies to be quantified. Studies are carried out on the future Great Britain power system with different wind energy penetration levels and frequency response requirements. The impact of the uncertainty associated with the quantity of wind plants being online and the energy recovery effect are also analysed. The results demonstrate that the benefits of frequency response support from wind plants may be significant, although these are system specific. The proposed model could also inform the development of grid codes, market mechanisms and business cases associated with the frequency response support from wind plants.**

***Index Terms*— Wind generation, inertia response, primary frequency response, unit commitment, power system dispatch.**

NOMENCLATURE

A. Constants

$\pi(n)$	Probability of reaching node *n*
$\mathcal{G}$	Set of thermal generators.
$\mathcal{S}$	Set of storage units.
$\mathcal{N}$	Set of nodes on the scenarios tree.
c^{LS}	Value of lost load (£/MWh).
$P_{g(s)}^{max}$	Capacity of thermal unit *g* (or storage unit *g*) (MW).
$R_{g(s)}^{max}$	Maximum primary frequency response capability of thermal unit *g* (or storage unit *s*) (MW).
$f_{g(s)}^{F}$	The proportion of the spinning headroom that can contribute to frequency response provision.
f_{w}^{F}	The proportion of curtailed wind that can contribute to frequency response provision.
K_{add}^{WN}	Ratio between additional primary frequency response requirement and synthetic inertia provision of WPs.
T_d	Delivery time of primary frequency response (s)
H_g	Inertia constant of thermal unit g (s).
H_{SI}^{n}	Candidates of time constant of synthetic inertia from WPs with tuneable controller (s)
D	Load damping rate (1/Hz)
Δf_{max}	Frequency deviation limit in nadir (Hz).
Δf_{max}^{ss}	Frequency deviation limit at steady state (Hz).
Δf_{DB}	Frequency deadband of governor (Hz)
T_d	Delivery time of frequency response (s)
$RoCoF_{max}$	Maximum rate of change of frequency (Hz/s).
f_0	Nominal frequency level (Hz)
ΔP_L	The capacity of largest plant outage (MW)
Δf_{max}	Maximum frequency deviation requirement in Nadir (Hz).
Δf_{max}^{ss}	Maximum frequency deviation requirement at quasi steady state (Hz).

B. Semi-constants (fixed with respect to Linear Program but variable between timesteps)

$P^{D}(n)$	Total demand at node *n* (MW).

C. Decision variables

$P_{online}^{WN}(n)$	Total capacity of online WPs at node n (MW).
$P^{WC}(n)$	Wind curtailment at node n (MW).
$R_{g(s)}(n)$	Primary frequency response provision from thermal unit g (or storage unit s) at node n (MW).
$R_{w}(n)$	Primary frequency response provision from WPs at node n (MW)
$H_{conv}(n)$	Total inertia provision from conventional plants at node n (MWs/Hz).
$H_{wind}(n)$	Total inertia provision from WPs at node n (MWs/Hz).
$R^{*}(n)$	Amount of primary frequency response at node n(MW)
$H^{*}(n)$	Amount of system inertia at node n (MW)
$H_{SI}(n)$	Time constant of synthetic inertia at node n (s).
$R_{add}^{WN}(n)$	Additional primary frequency response requirement due to SI provision from WPs at node n (MW).
$N_{g(s)}^{up}(n)$	Operation status (0/1 for Offline/Online) of thermal unit g (or storage unit s) at node n.
$N_{SI}^{n}(n)$	Binary variable to decide the time constant of synthetic inertia from WPs with tuneable controller at node n.

I. INTRODUCTION

The integration of a large share of renewable energy resources (RES) increases requirements for various ancillary services to support real-time balancing of demand and supply. For example, although variable speed wind turbines (VSWTs) show significant advantages over fixed speed wind turbines [1] (e.g. high operational flexibility), they are generally unresponsive to the system frequency [2]. Therefore, as wind generation displaces conventional plant production, the system inertia provided by rotating mass will be reduced, causing concerns over frequency stability [3] [4].

On the other hand, a significant amount of rotational energy is stored in wind plants (WPs). Extensive research has been conducted to investigate the capability of VSWTs to provide frequency response support. A supplementary control loop could be incorporated into the controller of WPs to provide frequency response similar to conventional plants. Authors in [5] show that VSWTs with proposed controller could even provide more synthetic inertia (SI) than fixed speed wind turbines. The SI and primary frequency response (PFR) capabilities of different turbine technologies are assessed in [6], and the maximum temporary extra active power supply from a multi-megawatt VSWT is quantified in [7]. In addition, the delivery of frequency response support from HVDC connected offshore WPs is discussed in [8] [9].

The impacts of frequency response support from WPs on system frequency performance have been assessed in different systems. The results suggest that the rate of change of frequency (RoCoF) and frequency nadir could be significantly improved, but it depends on the system specifications and the design of the controller. The study in [10] analyses the impact of WPs participating in the U.S. Western Interconnection and concludes that wind energy penetration level and PFR capability of conventional plants are the key factors in determining the effectiveness of frequency response support from WPs. The impacts of different parameters associated with SI and PFR on the system frequency response performance are analysed in [11]. The results show that very aggressive design of SI and PFR may provide limited benefits in reducing frequency nadir, but cause delay in reaching steady-state condition. Moreover, the recovery period following SI provision could cause a second frequency nadir, so the authors in [12] propose a modified control algorithm to mitigate this effect.

Although the technical performance of frequency response support from WPs has been widely studied, its impacts on generation scheduling and the economics of system operation are not yet fully understood. Since there are alternative options (e.g. demand side response [13]) to alleviate concerns over frequency stability, it is important to fully understand its economic and environmental benefits. Previous studies have assessed the benefits of WPs in providing secondary and tertiary reserves. The results suggest that secondary reserve provision from WPs could effectively reduce the system operation cost even when WPs are compensated by the lost opportunity cost [14] [15], while tertiary reserve provision is beneficial only for the case when there is a high tertiary reserve requirement [16]. However, very little work has been conducted on assessing the system benefits and implications of SI and PFR provision from WPs.

There are some characteristics associated with WPs in providing frequency response support, which are distinguished from conventional plants. Firstly, the authors in [17] [18] point out that there is uncertainty associated with the quantity of WPs being online for a given level of system wise wind generation, leading to a challenge associated with estimating the aggregated SI from WPs. Secondly, as discussed in [11] [12], additional PFR may be required to support the recovery of original turbine speed. The system scheduling process needs to take into account of the recovery effect in order to retain the system security. Finally, in order to provide PFR, WPs need to be de-loaded from their maximum operation point. The cost associated with de-loading and benefits from PFR provision need to be explicitly balanced in the system scheduling process and in fact different system conditions actually require different amounts of PFR provision from WPs. Therefore, it is important to incorporate these characteristics into an optimal generation scheduling model. In this context, this paper develops a novel framework to incorporate frequency response support, provided both by conventional plants and WPs, into the system scheduling model and therefore enables the benefits of frequency response support from WPs to be quantified. We identify the key contributions:

1. This paper proposes a model for the aggregated SI provision from WPs that explicitly considers the uncertainty in the quantity of WPs being online at each point in time and the additional PFR required due to the recovery effect.
2. Furthermore, the paper proposes a novel assessment framework, which extends the model in [19], to take into account, for the first time, SI and PFR provision from WPs. The key characteristics of SI and PFR provision from WPs as well as the tuneable controller of SI are explicitly modelled in the proposed framework.
3. The benefits of frequency response support from WPs are assessed in the context of the future GB system. The impacts of the uncertainty associated with the quantity of WPs being online and the recovery effect are investigated. The need for frequency response support from WPs and the corresponding design criteria for WPs controllers are shown to be system-specific. The case studies can inform the development of future grid codes, market mechanisms and business cases associated with fast frequency response services from WPs.

The rest of this paper is organized as following: Section II discusses the key characteristics of frequency response support from WPs and presents the modelling that can be used in the scheduling model. Section III describes the proposed scheduling model, which explicitly takes into account of SI and PFR provision from WPs. The proposed tool is applied in Section IV to assess the benefits of frequency response support from WPs, while Section V concludes the paper.

II. Modelling of Frequency Support from WPs

With appropriately designed frequency controllers, WPs could provide fast frequency response similar to that of conventional plants. The SI controller, similar to the inertia response of conventional plants, responds to RoCoF and provides transient response, which is instantaneous and most effective during fast frequency changes. Droop control (PFR), on the other hand, provides longer-term response, which is delivered over time and is most effective in relatively slow frequency changes. Combined inertia and PFR could reduce both the transient excursions of the frequency and its steady-state error [6]. This section discusses the key characteristics of SI and PFR provision from WPs and presents relevant models to capture these characteristics. In this paper, the effects associated with delays in RoCoF measurement and turbine actuation, together with ramp rate constraints impacting the ability of WPs to provide SI and PFR, are not explicitly modelled. On the other hand, the extreme ranges of the ability to provide SI are considered: from a case in which WPs cannot provide any inertia to a case in which the level of SI of WPs is similar to conventional plants [2].

A. Synthetic Inertia Provision from Wind Plants

According to the principal of inertia control, a control loop could be incorporated into WPs controller to supple additional power from WPs ($\Delta P_W^{Inertia}$) based on the derivative of frequency change (1). Unlike conventional plants, SI of WPs is dominated by the design of the controllers, which should be optimized to maximise the system benefits. Moreover, there are proposals to develop a tuneable controller for SI provision, allowing the time constant to be modified according to the system needs under different system conditions.

$$\Delta P_W^{Inertia} = -\underbrace{K_{inertia}}_{2*H_{SI}} \frac{\partial \Delta f}{\partial t} \tag{1}$$

The SI provided by WPs depends on a number of stochastic variables, including wind speed, wind turbulence, mechanical states of the drive train and so on. However, the aggregated SI from WPs in the system may be obtained by averaging SI for individual WPs [17]. In fact, the quantity of WPs being online is the key factor in determining the aggregated SI. The work in [18] illustrates the uncertainty associated with the quantity of WPs being online for a given level of system-wise wind generation, based on historical data from wind farms in Ireland. Fig.1 shows the maximum, average and minimum quantity of WPs being online for a given level of wind generation. This raises the question of the reliability associated with the reliance on SI, particularly given the risk-averse attitude of the system operators.

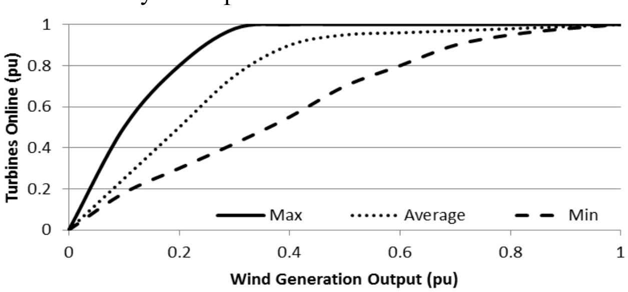

Fig.1 Variable speed wind turbines operating above minimum speed

Below rated wind speed, the delivery of SI is followed by a recovery period, causing a temporal reduction in power output of WPs below the original operation point. As studied in [11], the recovery period could delay the system frequency from reaching the steady-state condition, even causing a second frequency nadir. In the Hydro Quebec system [20], the specification requires the maximum generation reduction during the recovery phase to be lower than 20% of its nominal power. In fact, as emphasized in [12], the recovery effect of SI may lead to an increased demand for PFR to retain the system security. However, it is difficult to precisely qualify the additional PFR that should be scheduled to supply the required energy for the acceleration of WPs. There are also other types of controllers designed to reduce or completely eliminate the recovery effect. To demonstrate the impact of energy recovery and the benefit of reducing it, simplified relationships between the time constant of SI and the additional PFR in the steady state are assumed as in Fig.2:

$$R_{add}^{WN} = K * H_{SI} * P_{online}^{WN}(n) \tag{2}$$

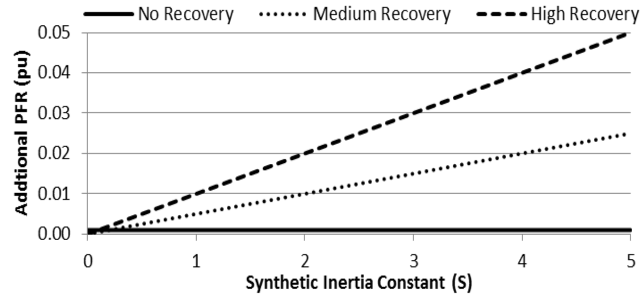

Fig.2 Assumptions on recovery effect of SI provision

B. Primary Frequency Response Provision from Wind Plants

For PFR, a droop control (K_{droop})can be incorporated into the WPs controller to increase the power supply from WPs (ΔP_W^{PFR}) according to the frequency change:

$$\Delta P_W^{PFR} = -K_{droop}\Delta f \tag{3}$$

Similar to conventional plants, WPs need to be de-loaded from the optimal operating point to provide sufficient headroom in order for the droop function to be active in under-frequency events. The PFR provision from WPs (R_w) is limited by the curtailed wind power (P^{WC}), which is the difference between the maximum potential output and the actual output of WPs:

$$R_w \le f_w^F * P^{WC} \tag{4}$$

A headroom of 5% or 10% is generally chosen in the technical studies [2]. However, in order to achieve optimal operation, the costs of de-loading WPs and the benefits of PFR provision need to be balanced, and the optimal amount of PFR provision actually varies under different system conditions.

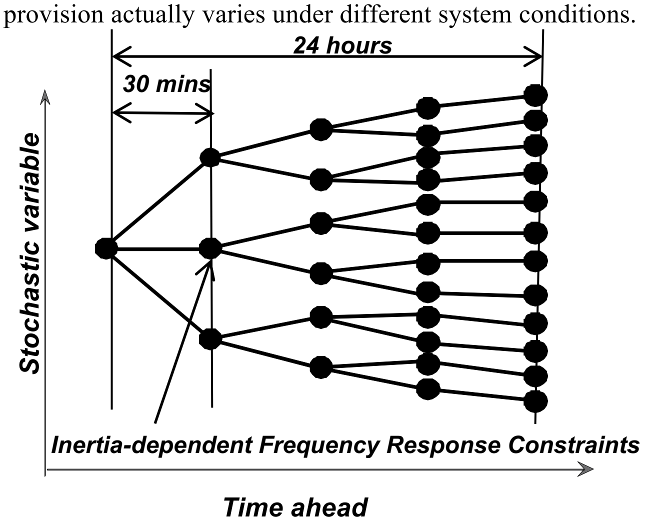

Fig.3 Schematic of a typical scenario tree in SUC with inertia-dependent frequency response requirements

III. Methodology

To cope with the increased penetration of RES, a number of advanced non-deterministic scheduling methods have been proposed, such as robust optimization [21] and interval optimization [22]. Among these methods, scenario-based stochastic methods are shown to represent the dynamic process of uncertainties and decisions more appropriately, but suffer computational burden due to the large number of considered scenarios [23]. However, authors in [24] [25] show that, with careful selection, reduced number of scenarios may be used while providing high-quality scheduling decisions. This section introduces a multi-stage stochastic scheduling model with explicit consideration of the key characteristics of frequency response support from WPs discussed in Section II. The unit commitment (UC) and economic dispatch (ED) are solved over a scenario tree (Fig.3). In each node of the scenario tree, system frequency dynamic evolution is mapped into the scheduling model through constraints associated with (a) RoCoF, (b) nadir frequency and (c) steady-state frequency. The simulations are carried out using a rolling planning approach, performing a complete stochastic unit commitment (SUC) calculation with a 24-h horizon in half-hourly timesteps, and discarding all decisions beyond the root node ones. In the next time step, realizations of some uncertain variables become available, which may be different from any existing scenario. An updated scenario tree covering a 24-h time horizon is then built; UC and ED decisions are adjusted with inter-temporal constraints maintained.

A. Scenario Tree

A quantile-based scenario selection method is adopted in the framework. This method is developed in [25] by constructing and weighting a scenario tree based on user-defined quantiles of the distribution of the forecasting error. The normalized wind level is assumed to follow a Gaussian AR(2) process with half-hourly timesteps, which is then transformed into a non-Gaussian wind power output with a range from zero to the installed capacity of WPs [25]. The probability distribution of outages is derived by using a capacity outage probability table (COPT). The cumulative distribution function (CDF) $C(x;n)$ of the net demand is the total system demand minus the convolution of the probability distribution function (PDF) of realized wind production with the negative cumulative nodal COPT. The q^{th} quantile of the net demand distribution can be calculated as $x: C(x;n) = q$ by using a numerical root-finding algorithm. The nodal probability $\pi(n)$ can be obtained from user-defined quantiles by using the method (Trapezium) introduced in [25].

B. Stochastic Unit Commitment Formulation

This paper extends the SUC model in [19] to incorporate frequency response support from WPs. The model is formulated as a mixed integer linear programing (MILP) problem. The detailed equations below are referred from the Appendix in [19]. The objective is to minimize the expected operation costs (A.1), including the generation costs (variable cost, no-load cost and start-up cost) and the load shedding costs. The optimization is subject to the load balance constraint (A.2), the constraints for thermal units (including minimum/maximum generation (A.10), commitment time (A.11), minimum up/down time (A.13) - (A.14), ramping rates (A.16) - (A.17), fast frequency response capability (A.18) - (A.19)) as well as constraints for storage units (A.20) - (A.25). Moreover, equations (7), (9.b)-(9.i) and (12), developed in the next sub-section, are incorporated into the model to ensure frequency response adequacy with the contribution from WPs.

C. Fast Frequency Response Requirements with Frequency Response Support from WPs

The aim of fast frequency response is to contain the dynamic evolution of frequency after a generator outage within defined security thresholds. In GB, this is specified by the Security and Quality of Supply Standard [26]. Three criteria are used to set the security standards for the initial transient evolution of the frequency (Fig.4): (1) RoCoF, (2) Nadir frequency and (3) Steady-state frequency. The RoCoF achieves its highest absolute value just after a disturbance occurs; initially the frequency drop is only limited by the inertia response of conventional generators and WPs. The present standard prescribes that the RoCoF should not exceed 0.25Hz/s. Furthermore, the PFR has to limit the frequency above a minimum value set to 49.2 Hz, in the case of the largest infeed loss. An extended provision of PFR enables meeting the steady-state condition that the frequency should stabilize above 49.5 Hz within 60s.

In this sub-section, we propose a formulation to explicitly include the requirements on frequency dynamic evolution within the SUC formulation introduced in the section III.B. The differential equation (5) is mapped into the SUC model by considering three characteristic periods in the form of constraints associated with the three criteria discussed above. The proposed constraints correspond to a single node in the scenario tree; hence the node label 'n' is suspended.

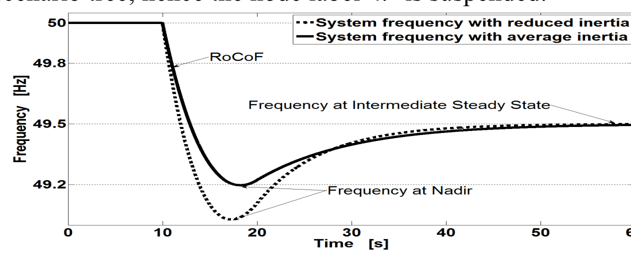

Fig.4 System frequency evolution after a contingency

The time evolution of system frequency deviation after a contingency can be described by a first order ODE:

$$\underbrace{(2 * H_{Conv} + 2 * H_{Wind})}_{2H^*} * \frac{\partial \Delta f(t)}{\partial t} + D * P^D * \Delta f(t) = \underbrace{\sum_{g,s \in \mathcal{G},\mathcal{S}} \Delta P_{g(s)}(t) + \Delta P_W^{PFR}(t) - \Delta P_L}_{\Delta P^*} \quad (5)$$

where $\Delta P_{g(s)}/\Delta P_W^{PFR}$ [MW] describes the extra power provided by conventional generators(storage) /WPs following the generation loss.

In this paper, the delivery of PFR is assumed to be linearly increasing with time and thus characterized by a fixed slope until scheduled PFR is delivered at T_d [27]. This model also includes a dead-band Δf_{DB} that prevents unnecessary response to relatively small frequency deviations. Therefore, the delivery of PFR can be modelled as:

$$\Delta P^* = \begin{cases} 0 & if\ t < t_{DB} \\ \dfrac{\overbrace{R_{g(s)} + R_w}^{R^*}}{T_d} * (t - t_{DB}) & if\ T_d + t_{DB} \geq t \geq t_{DB} \\ R_{g(s)} & if\ t \geq T_d + t_{DB} \end{cases} \quad (6)$$

where t_{DB} represents the time when frequency deviation reaches the dead-band Δf_{DB}.

1) Rate of change of frequency (RoCoF)

The time period that involves the RoCoF limit is only the first instance following a generation loss. In this short interval, PFR is still not activated, as the deviation of frequency is very small. Hence, the minimum level of system inertia H^*, required to satisfy the maximum RoCoF requirement ($RoCoF_{max}$) is found to be:

$$H^* = \frac{\sum_{g\in\mathcal{G}} H_g * P_g^{max} * N_g^{up} + H_{SI} * P_{online}^{WN}}{f_0} \geq \left|\frac{\Delta P_L}{2*RoCoF_{max}}\right| \quad (7)$$

2) Nadir Frequency

The frequency nadir is defined as the minimum value of frequency reached during the transient period. The nadir depends on system inertia and PFR. The system is assumed to operate at nominal frequency (50Hz) in the pre-contingency state, and the delivery of frequency response is described by (6). By integrating (5), the frequency nadir can be calculated:

$$|\Delta f_{nadir}| = \Delta f_{DB} + \frac{\Delta P_L{}'}{D'} + \frac{2R^* * H^*}{T_d * D'^2} log\left(\frac{2R^* * H^*}{T_d * D' * \Delta P_L{}' + 2 * R^* H^*}\right) \quad (8)$$

where $D' = D * P^D$, $\Delta P_L{}' = \Delta P_L - D' * \Delta f_{DB}$, $t' = t - t_{DB}$ and $R^* = \sum_{g,s\in\mathcal{G},S} R_{g(s)} + R_w$.

According to [19], the frequency nadir requirement with SI contribution from WPs can be found to be:

Proposition: $|\Delta f_{nadir}| \leq \Delta f_{max}$ if the following mixed integer linear constraints are satisfied:

$$\begin{cases} \dfrac{\sum_{g\in\mathcal{G}} H_g * P_g^{max} * y_g + H_{SI} * P_{online}^{WN} * R^*}{f_0} \geq k^* & (9.a) \\ -M * \left(1 - N_g^{up}\right) \leq y_g - R^* \leq M * \left(1 - N_g^{up}\right) & (9.b) \\ -M * N_g^{up} \leq y_g \leq M * N_g^{up} & (9.c) \end{cases}$$

where y_g is an additional variable, M is a large number and k^* is the unique solution from

$$\frac{2k^*}{T_d} \cdot log\left(\frac{2k^*}{T_d * D' * \Delta P_L{}' + 2k^*}\right) = D'^2(\Delta f_{max} - \Delta f_{DB}) - D' * \Delta P_L{}' \quad (9.d)$$

In the case of tuneable SI controller, where the time constants of SI (H_{SI}) are allowed to be chosen from pre-defined candidates (H_{SI}^1, H_{SI}^2 ... H_{SI}^N) under different system conditions to minimize the overall operation costs, constrain (9.a) becomes nonlinear. This paper introduces additional continuous variables (y_{SI}^n) as well as binary variables ($N_{SI}^1, N_{SI}^2 ... N_{SI}^N$), and applies the reformulation method in [28], so that constraint (9.a) can be replaced a set of MILP constraints below:

$$\frac{\sum_{g\in\mathcal{G}} H_g * P_g^{max} * y_g + \sum_{n\in\{1,2...N\}} P_{online}^{WN} * y_{SI}^n}{f_0} \geq k^* \quad (9.e)$$

for all $n \in \{1,2 ... N\}$

$$-M * (1 - N_{SI}^n) \leq y_{SI}^n - H_{SI}^n * R^* \leq M * (1 - N_{SI}^n) \quad (9.f)$$

$$-M * N_{SI}^n \leq y_{SI}^n \leq M * N_{SI}^n \quad (9.g)$$

$$\sum_{n\in\{1,2...N\}} N_{SI}^n = 1 \quad (9.h)$$

$$H_{SI} = \sum_{n\in\{1,2...N\}} N_{SI}^n * H_{SI}^n \quad (9.i)$$

3) Steady-state frequency

The steady-state condition essentially depends on the total amount of PFR delivered at T_d. Given a steady-state frequency deviation limit Δf_{max}^{ss}, this frequency deviation can be found, by assuming in (5) that RoCoF is effectively zero:

$$|\Delta f^{ss}| = \frac{\Delta P_L - R^*}{D * P^D} \leq \Delta f_{max}^{ss} \quad (10)$$

This allows quantification of the PFR reuqired to satisfy the steady-state frequency criterion as:

$$R^* \geq \Delta P_L - D * P^D * \Delta f_{max}^{ss} \quad (11)$$

There may exist additional PFR (R_{add}^{WN}) due to the provision of SI from WPs and therefore the PFR requirement in the steady state can be described as:

$$R^* \geq \Delta P_L - D * P^D * \Delta f_{max}^{ss} + R_{add}^{WN} \quad (12)$$

IV. System Benefits of Frequency Response Support from Wind Plants

This section applies the model proposed in section III to quantify the benefits of frequency response support from WPs. The assessment is aimed at understanding the value of SI provision, the impact of uncertainty associated with the quantity of WPs being online, the importance of controlling WPs speed recovery, the advantages of tuneable controller as well as the benefits of combined provision of SI and PFR.

A. Description of the System

This sub-section describes the system and the assumptions used in the case studies. The annual system operation is simulated in a system [25], designed to represent a possible configuration for GB 2030 scenario. The maximum demand and total conventional plants capacity are 60 GW and 70 GW, respectively. The installed wind capacity is varied, selecting from 20/40/60GW, corresponding to 20%/40%/60% wind energy penetration. A 2.6 GW pump-storage with 10GWh energy capacity and 75% round-trip efficiency is also included. The key characteristics of conventional plants are presented in TABLE I [13]. The reference settings for delivery time($T_d = 10s$) , RoCoF limit ($RoCoF_{max} = 0.25\ Hz/s$) , frequency dead-band ($\Delta f_{DB} = 15mHz$) and load-damping rate ($D = 1\%/Hz$) are chosen according to GB standards [26]. The impact of a relaxed RoCoF limit ($RoCoF_{max} = 0.5\ Hz/s$) [29] is assessed. In the base cases, the average number of online WPs is utilized [17]; the time constant of SI is assumed to be 5s; and the recovery effect is ignored. The optimization was solved by FICO Xpress through C++ application via BCL.

TABLE I
Characteristics of Thermal Plants

	Nuclear	*Coal*	*CCGT*	*OCGT*
Number of plants	6	40	70	30
Rated Power (MW)	1800	500	500	200
Min Stable Gen (MW)	1800	250	250	50
No-load cost (£/h)	0	3364	7809	8000
Marginal cost (£/MWh)	7	72	51	110
Startup cost (£/start-up)	n/a	90000	32000	0
Startup time (h)	n/a	6	4	0
Min down time (h)	n/a	4	4	0
Inertia Constant (s)	5	5	5	5
Max Response (MW)	0	75	75	40
Response Slope	0	0.3	0.4	0.6

B. System Benefits of SI Provision from WPs

This subs-section assesses the system benefits of SI provision from WPs, in terms of reducing the cost of frequency response provision and achieving a high percentage of energy demand supplied by WPs. Firstly, Fig.5 shows the annual cost associated with provision of frequency response with different installed capacities of WPs. The annual cost is calculated by comparing the total system operation costs with and without fast frequency response requirements. When 60GW of WPs is installed, the annual cost increases by about 10 times when compared with the system without WPs. This increase is driven by the need to part-load conventional plants to provide frequency response and moreover by the increase in energy production by conventional plants due to wind curtailment. The relaxation of the RoCoF limit from 0.25Hz/s to 0.5Hz/s is shown to be capable to significantly alleviating the challenge of frequency response provision. In fact, with a relaxed RoCoF limit, the system can integrate 20GW of WPs without causing a large increase in the cost of frequency response provision. However, the cost still increases more than 3 times when 60GW of WPs are installed.

SI is shown to be more effective in reducing the cost of frequency response provision. With SI capability, marginal increase in the cost would occur when upto 40GW of WPs is installed, although it cannot completely eliminate the increased cost in the system with very high capacity of WPs. The results also suggest that, with SI capability from WPs, the benefit of relaxing RoCoF limit is limited.

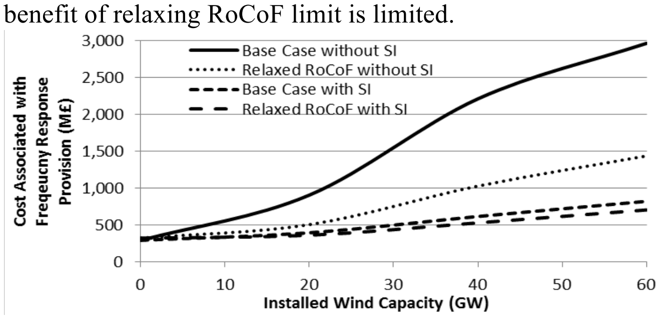

Fig.5 Impact of WPs on the cost associated with frequency response provision

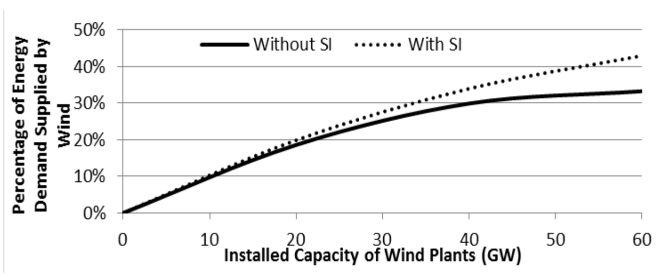

Fig.6 Impact of SI on the ability of the system to reach high percentage of energy demand supplied by wind

SI capability of WPs also plays an important role in achieving a high percentage of energy demand supplied by WPs. Fig.6 shows how the percentage of energy demand supplied by WPs varies with different installed capacities of WPs. The results suggest that, without SI capability, the percentage increases linearly with the installed capacity of WPs, but saturates after reaching 30%. In particular, when the wind capacity increases from 40GW to 60GW, the percentage of energy demand supplied by WPs only increases by 3%, implying a large amount of wind curtailment. On the other hand, with SI capability, the percentage of energy demand supplied by WPs could increase by 10%, reaching over 40%.

C. Value of SI with Different Technology Penetration Levels

This sub-section quantifies the value of equipping WPs with SI capability. Since it is not likely that all WPs will provide SI in the future, especially for the WPs these are already in operation or under construction, this sub-section focuses on the marginal operation cost saving as a function of the volume of WPs with SI capability. The marginal saving at each technology penetration level is calculated by dividing the additional operation cost saving by the additional capacity of WPs with the SI capability. Given a cost associated with SI capability, the results can be used as a reference in a cost-benefit analysis to determine the amount of WPs to be equipped with SI capability.

As shown in Fig.7, the value of SI is in general high with moderate technology penetration levels, but decreases linearly with increased capacity of WPs capable of providing SI. The value shows a significant jump when the installed capacity of WPs increases from 20GW to 40GW; while the further increase is not significant when the capacity increases to 60GW. The results also suggest that it may not be necessary to require all the WPs to provide SI, as the marginal value is very low after 30GW of WPs equipped with SI capability.

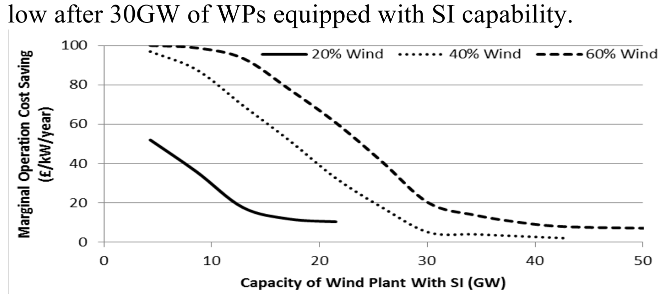

Fig.7 Marginal Operation Cost Saving from SI (with 0.25Hz/s RoCoF)

As already discussed in GB, a relaxation of the RoCoF limit could be implemented to support the integration of RES. This might reduce the need and value for WPs to provide SI. Therefore, a similar study is carried out with a relaxed RoCoF limit. The results in Fig.8 suggest that the value of SI provision would be reduced by a factor of 5. However the first 10GW of WPs could still reduce the annual operation cost by 20£/kW in the system with more than 40GW of WPs.

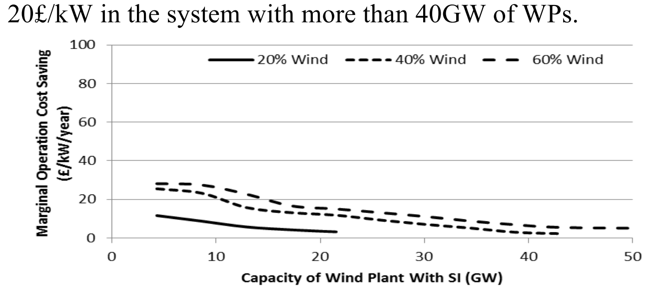

Fig.8 Marginal Operation Cost Saving from SI (with 0.5Hz/s RoCoF)

The results in Fig.7 and Fig.8 show that, given an annualised cost associated with SI capability, the optimal amount of WPs to be equipped with SI capability is system specific. The installed capacity of WPs and the frequency response requirements are identified as the key driving factors.

D. Impact of Uncertainty Associated with the Quantity of WPs being Online

As discussed in Section III, there exists uncertainty associated with the quantity of WPs being online. The results presented so far are based on an average of this value. However, due to the risk-averse attitude, the system operators may make conservative assumptions regarding the quantity of WPs being online. Therefore, this sub-section analyses the impact of this uncertainty on the benefit of SI provision. Fig.9 shows the operation cost saving in the system with 40GW of WPs, by using assumptions of maximum, average and minimum quantity of WPs being online (as shown in Fig.1). The results are presented as the ratios of the value with the maximum/average/minimum quantity of WPs being online over the value with the average quantity of WPs being online. With a low penetration of WPs with SI capability, the conservative assumption could reduce the benefit of SI provision by 40%, when compared with the case using the average quantity. However, with increased penetration of WPs with SI capability, this uncertainty shows much less impact. In the case that all the WPs are capable to provide SI, a conservative assumption only leads to 5% benefit reduction. The results also provide evidence that in a system with a relatively low penetration of WPs with SI capability, there is significant value in providing information to system operators regarding the actual quantity of WPs being online.

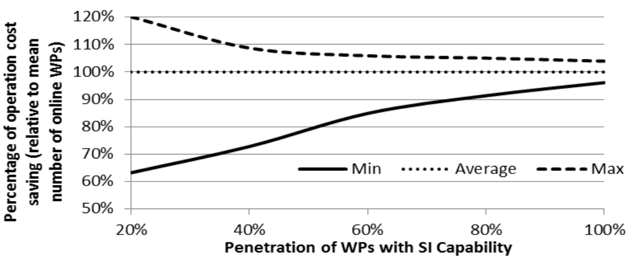

Fig.9 Impact of uncertainty associated with online WPs on the benefit of SI.

E. Impact of Recovery Period of Wind Plant Speed

Another challenge associated with SI provision from WPs is the recovery period of the WPs original speed. Without careful design of the controller, this effect may have a detrimental impact on the system operation. This sub-section analyses this effect in the system with 40GW of WPs, with particular focus on the impact of different time constants of SI.

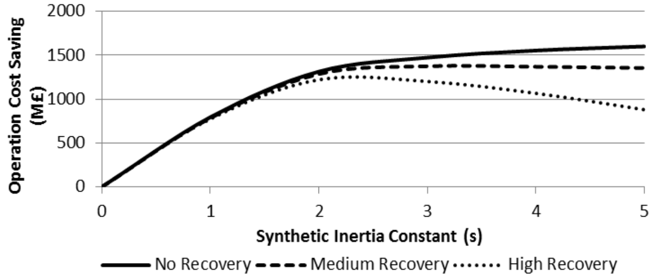

Fig.10 Impact of recovery effect on the value of SI (with 0.25Hz/s RoCoF)

The results in Fig.10 show that the more severe the recovery effect is, the less benefit SI brings. However, the reduction is in general moderate in the system with a tight RoCoF limit. This is due to the fact that a tight RoCoF limit actually constrains the system operation and large amount of conventional plants are committed only to provide the required inertia. These part-loaded plants could provide sufficient headroom to supply the additional PFR due to SI provision of WPs, without incurring additional costs.

Similar studies are carried out for the system with a relaxed RoCoF limit. The results in Fig.11 show that the recovery effect could largely offset the benefit of SI provision if the controllers were designed to be very aggressive. Moderate SI contribution from WPs helps to reduce RoCoF and secure the frequency nadir, while the resulting additional PFR in the steady-state is moderate and could be easily met. On the other hand, very aggressive design leads to a significant increase in the cost associated with the supply of the additional PFR in the steady state. This cost may even exceed the benefit that SI brings in reducing RoCoF and secure the frequency nadir, actually causing a reduction in the overall benefit.

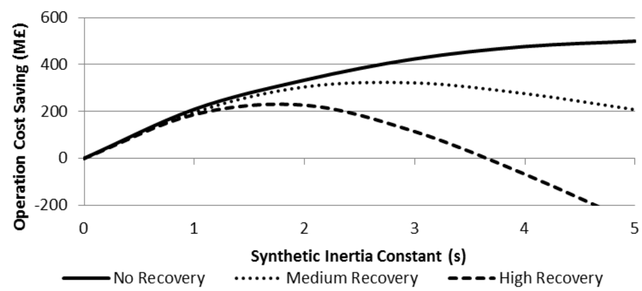

Fig.11 Impact of recovery effect on the value of SI (with 0.5Hz/s RoCoF)

The results shown in Fig.10 and Fig.11 also suggest that there exists an optimal time constant of SI which would achieve the maximum operation cost saving. This optimal time constant depends on the magnitude of the recovery effect and the frequency response requirements. It is also worth noting that under relaxed RoCoF, the maximum operation cost saving is £500M without the recovery effect but only £200M with a high recovery effect. This suggests a significant benefit in designing an SI controller with a reduced recovery effect, as proposed in [30].

There are proposals to develop a tuneable controller for SI provision, allowing the time constant to be modified according to the system needs under different system conditions. Table II compares the system operation cost saving for a fixed SI controller with an optimal time constant and a tuneable SI controller with time constant selected from {1,2,3,4,5}in the scheduling process. The result suggests a considerable benefit for a tuneable controller over a fixed controller, especially when there exists a severe recovery effect.

TABLE II
OPERATION COST SAVING OF DIFFERENT SI CONTROLLERS

	Fixed Controller	***Tuneable Controller***
No Recovery (£M)	500	500
Recovery_1 (£M)	322	406
Recovery_2 (£M)	224	338

F. Value of Combined Provision of SI and PFR from WPs

This sub-section assesses the value of WPs in providing combined SI and PFR in the system with 40GW of WPs. The operation cost savings for SI only, PFR only and SI+PFR are shown in Fig.12. With tight RoCoF limits, the capability of WPs to provide PFR has very limited value, since the system operation under this condition is constrained by the RoCoF limit. On the other hand, with relaxed RoCoF, PFR only could achieve similar savings to SI only, while the combined provision would lead to a further 10% saving.

The above results suggest that combined PFR and SI would deliver marginal additional benefits when compared with control schemes that deliver SI only. However, as already discussed, the recovery effect may lead to an increase in PFR requirements in the steady state, which may make the combined provision more desirable. Fig.13 shows that, with high recovery effect, the maximum saving is increased from £1200M in SI only to £1650M in the combined provision. In this particular case, the combined provision almost eliminates the recovery effect, since it achieves a similar operation cost saving to the case without a recovery effect (Fig.10). Moreover, the combined provision also impacts the optimal time constant of SI, which is changed from 2.2s in SI only to 3.8s in the combined provision.

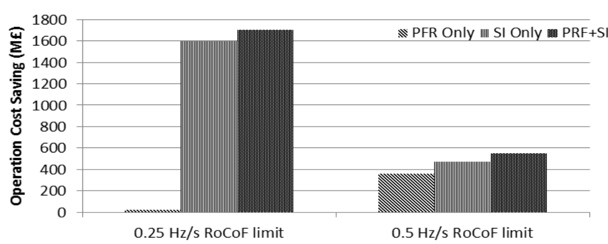

Fig.12 Operation Cost Saving from Frequency Support from WPs

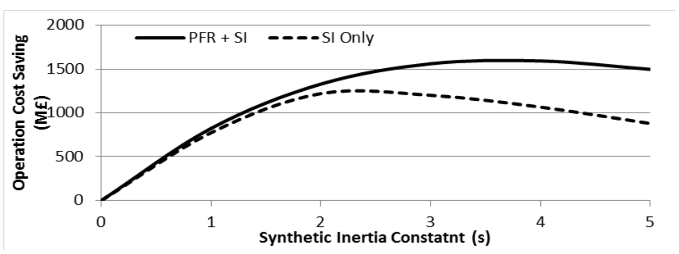

Fig.13 Impact of recovery effect on the value of combined SI and PFR

V. Summary and Discussion

This paper proposes a novel stochastic scheduling formulation, taking into account the frequency response support from WPs. The proposed model is applied to assess the benefits of SI and PFR provision from WPs in the future GB electricity system with different installed capacities of WPs and frequency response requirements.

The results suggest that SI could effectively reduce the system operation cost. In addition, the marginal saving given by the SI provision from WPs is investigated. This could be used to support cost-benefit analyse for determining the amount of WPs to be equipped with SI capability. The relaxation of RoCoF limit significantly reduces the demand on SI provision from WPs. The impact of uncertainty associated with the quantity of WPs being online is shown to be very significant in systems with a low penetration of WPs with SI capability. Moreover, the effect of the recovery period is system-specific. There is a moderate impact in systems with a tight RoCoF limit. While in systems with a relaxed RoCoF limit, aggressive design of the SI capability could even increase the system operation cost. In fact, there exists an optimal time constant of SI that would achieve the maximum operation cost saving. This optimal value of time constant depends on the installed capacity of WPs, the magnitude of the recovery effect and the frequency response requirements. The results also show a significant benefit in reducing this recovery effect. A tuneable SI controller would lead to greater benefits than a fixed one, if the recovery effect is severe.

The analysis carried out also demonstrates that there would be no value for WPs in providing PFR in a system with the present tight RoCoF limit. But when the relaxed RoCoF is applied, PFR provision could achieve similar cost saving to SI provision. Combined provision of SI and PFR shows only marginal extra benefits over SI only. However, the additional PFR due to a severe recovery effect could significantly increase the demand for this combined provision.

Although the delay of RoCoF measurement, the delay of WT actuation and ramp rate limitation of WPs are not directly modelled, the results clearly demonstrates that in systems with tight RoCoF limits, the level of SI that WPs could provide in managing RoCoF constraint will be a major driver of its value. However, in systems with relaxed RoCoF constraints, the value of the SI provided by WPs will be driven by their contribution to frequency nadir management, not RoCoF constraints. In other words, in the former case the delays in RoCoF measurements, WT actuations times and ramp rates, will play a major role regarding the value of SI from WPs, while in the latter case, these delays may have less impact, as the value is driven by its contribution to frequency nadir and not by RoCoF constraints.

There are several possible areas in which this analysis can be enhanced. Firstly, this paper only considers the uncertainty associated with the quantity of WPs being online when determining the aggregated SI provision. In fact, as discussed in [30], a more detailed model could be developed by taking into account of the probability distribution of wind speeds and wind ramps. Further research is also needed to model more accurately the relationship between the SI provision and the additional PFR requirement in the steady state.

Secondly, future work should include the impact of transmission network constraints, which have been shown to be one of the main drivers of wind curtailment in some area. Increased wind curtailment, driven by the network constraints, may actually enhance the benefits of frequency response support from WPs. Moreover, the role and value of frequency response support from WPs could be system-specific. In particular, for large interconnected systems, the effect of reduced inertia is less significant than that in islanded systems. In this context, the proposed model could be applied in other systems and further identify the key drivers of value.

Finally, this paper focuses on quantifying the system value of the frequency response support from wind turbines, which is calculated through reduction in system operating costs. The proposed modelling framework considers the cost implication of de-loading generation plants (both conventional and wind plants) from maximum generation point in order to provide frequency response and reserve services, as the associated cost incurred are inherently included in the model. This model optimizes the operation of all generating units to achieve minimum overall system operation costs while maintaining demand-supply balance and meeting frequency response and reserve requirements. As the results clearly suggest that there would be a significant benefit from frequency response support from WPs, a market framework, similar to the inertia market in [31] and compensation schemes for lost opportunity cost in [32], should be developed to provide appropriate compensation to the owners of WPs for the provision of SI and FPR and corresponding opportunity cost. Moreover, as WPs are operated under subsidy schemes, the intersection between the market designs and the subsidy schemes requires further investigation.

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