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Challenges of Primary Frequency Control and Benefits of Primary Frequency Response Support from Electric Vehicles

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Abstract

As the integration of wind generation displaces conventional plants, system inertia provided by rotating mass declines, causing concerns over system frequency stability. This paper implements an advanced stochastic scheduling model with inertia-dependent fast frequency response requirements to investigate the challenges on the primary frequency control in the future Great Britain electricity system. The results suggest that the required volume and the associated cost of primary frequency response increase significantly along with the increased capacity of wind plants. Alternative measures (e.g. electric vehicles) have been proposed to alleviate these concerns. Therefore, this paper also analyses the benefits of primary frequency response support from electric vehicles in reducing system operation cost, wind curtailment and carbon emissions.

Keywords: Renewable energy, inertia, primary frequency control, electric vehicles.

1. Introduction

Traditionally, electricity system is dominated by large synchronized power plants, which provides inertia to support maintaining the system frequency to be in a narrow interval. However, as the increased penetration of wind generation, the system inertia declines as wind turbines are normally decoupled from electrical system and therefore unresponsive to frequency events. The lack of system inertia exacerbates the need for primary frequency response (PFR) in order to maintain the frequency within security boundaries and avoid, in the worst case, blackouts. The additional PFR will be primarily delivered

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through part-loaded plants, which not only lead to higher operation cost, but may also eventually compromise the ability of the system to absorb growing wind generation. In fact, the lack of system inertia already causes wind curtailment in Ireland, which limits the instantaneous non-synchronous generation penetration ratio below 50% [1]. Although the impact of reduced inertia on the system frequency performance has been widely studied [2] [3], its impact on the system operation and economics has not yet been fully understood.

As it is becoming clear that meeting the future needs for PFR solely by conventional plants might become very expensive and also potentially worsen the environmental performance of the system, these increased requirements may need to be supplied by other flexible resources, e.g. demand side response (DSR) [4]. As an important subset of DSR, electric vehicles (EVs) have significant flexibility in temporal patterns, facilitated by the inherent battery storage. The capability of EVs to provide PFR and its impact on the system frequency performance has been studied in [5] [6], while the associated economic benefit is analyzed in [7]. However, none of these above studies considered the increased PFR requirement driven by the high penetration of wind generation, which may lead to higher benefits of PFR support from EVs.

In this context, this paper implements an advanced stochastic scheduling model which directly considers the impact of reduced inertia on the PFR requirements. The model is applied to identify the challenges on primary frequency control (PFC) and quantify the economic and environmental benefits of EVs in providing PFR in the future Great Britain (GB) electricity system.

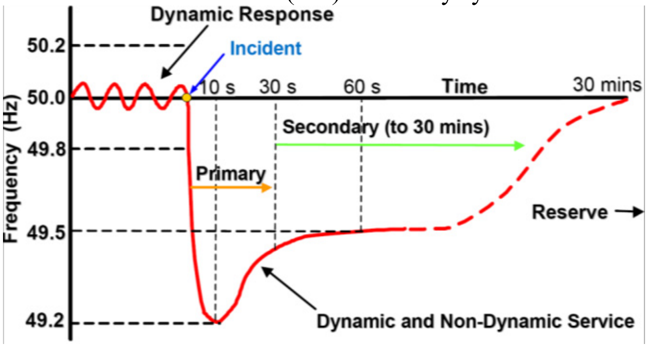

Figure 1 System frequency evolution after a contingency (National Grid)

2. Primary Frequency Control in the Future Great Britain Electricity System

2.1. Overview of primary frequency control in the Great Britain electricity system

An overriding factor in the power system operation is to maintain system security, i.e. to supply customers with electricity while meeting the quality of supply requirements at all times. Therefore, the balance between demand and generation must be continually maintained in order to keep the system frequency within a narrow range around nominal frequency. The GB Security and Quality of Supply Standard (GB-SQSS) requires frequency change to be maintained within ±0.2 Hz of the nominal frequency under normal operating conditions, while for a sudden generation loss upto 1800MW (1320 MW before April 1st 2014), the minimum frequency needs to be limited to 49.2 Hz with frequency restored to 49.5 Hz within 1 minute [8]. The system operator procures ancillary services to ensure that the system can withstand the largest credible outage. In particular, PFR is defined as the automatic increase in output or decrease in demand, in response to a fall in frequency that occurs in the period 0 to 10 seconds from the time of the frequency fall and is sustained for a further 20 seconds. PFR has the purpose of arresting the frequency fall, following a loss of generation, until secondary response becomes available.

The present requirement for PFR is represented in the form of curves that specify the necessary PFR for a given demand level and size of generation loss.

2.2. Impact of declining system inertia on the primary frequency control

The declining system inertia exacerbates the need for PFR in order to sustain the frequency performance. This section implements the model developed in [9] to demonstrate the impact of declining system inertia on the PFR requirement and the associated system cost. The equation (10) and (11) in [9] are proposed to ensure the frequency nadir within the statutory limit. Assuming that inertia constant of conventional plants $H=4.5s$ and wind plants do not contribute to system inertia, the system requirement for PFR can be calculated for various levels of demand, as well as for different levels of absorbed wind generation. As a demonstration, Figure 2 shows that the increased wind level could significantly increase the need for PFR, particularly during low demand periods. For example, when the system demand level is 30GW, in the system condition without wind generation, around 1.5GW PFR is required, while in the system condition with 20GW absorbed wind generation, more than 3.5GW PFR is required.

Annual system operation is then simulated by using the advance stochastic scheduling tool [9] to quantify the increased cost associated with PFR provision [10]. The annual cost of PFR provision is calculated by comparing the total system operation costs with and without fast frequency response requirements. The case study is carried out in one of the GB future scenarios with different installed wind capacity. The results in Figure 3 show that the annual cost of PFR provision increases significantly along with the increased capacity of wind plants. Moreover, there is a clear trend of accelerated increase after 20GW of wind plants are installed. In the case of 60GW installed wind capacity, this cost is 4 times of that in the system without wind plants.

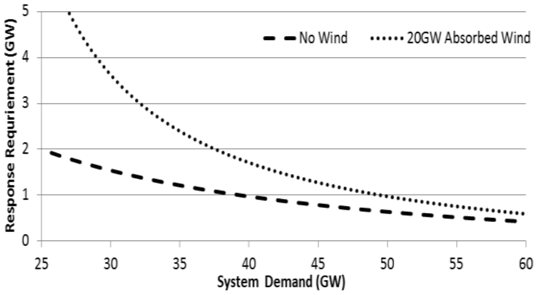

Figure 2 PFR requirement under different system conditions

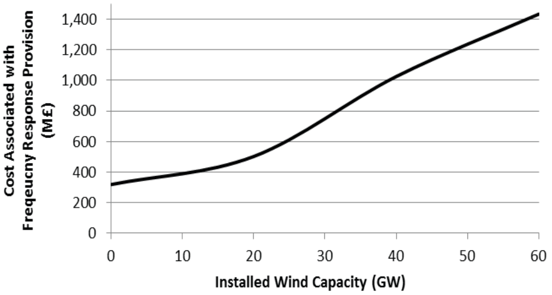

Figure 3 The cost associated with PFR provision

3. Benefits of Primary Frequency Response Support from Electric Vehicles

3.1. The potential of electric vehicles to provide primary frequency response support

As one of the key policy measures to further reduce carbon emissions, electrification of transportation has attracted growing attentions in recent years. By switching to EVs, carbon intensity of transport sector could be largely reduced. At the same time, there appears to be significant flexibility in temporal patterns of EVs, which could be used to provide ancillary services to support the operation of electricity system. In particular, EVs are capable to provide PFR under appropriate control strategy. As discussed in [11], EVs could provide PFR by adding a droop controller, which adjusts the EV charging power according to the change of frequency. Moreover, EVs have been shown to be capable of responding to frequency deviations in a much faster speed than conventional plants.

Figure 4 shows a proposed framework to enable EVs to provide PFR. The authors in [5] perform an assessment of PFR support from EVs in 2020 GB electricity system. The results show that EVs could effectively increase the frequency nadir after a contingency. The authors also identify that smart charging strategy leads to the best support of EVs on PFC. This is due to the fact that the challenges on PFC are more severe during low-demand/high-wind periods and smart charging strategy tends to schedule the charging of EVs during those periods, leading to more PFR contribution from EVs. Therefore, EVs under smart charging strategy could not only provide PFR support, but more importantly provide it during critical hours.

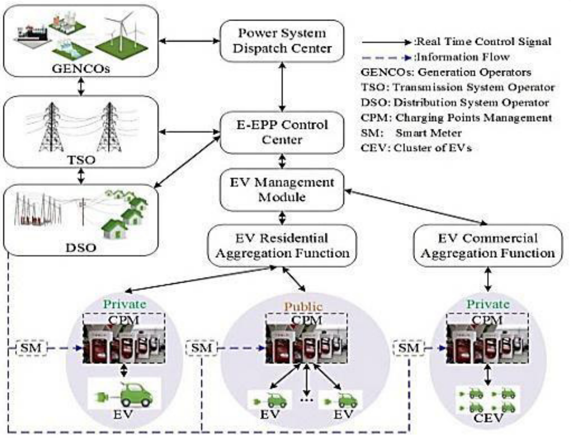

Figure 4 Framework of PFR Provision from EVs

3.2. Economic and environmental benefits of primary frequency response support from electric vehicles

As demonstrated in the previous sections, declining inertia would lead to a significant increase in both the required volume and the associated cost of PFR. The provision of PFR from EVs could effectively alleviate these challenges. This section implements the model developed in [9] to assess the economic and environmental benefits of PFR support from EVs.

The effective shape of EVs demand seen by large-scale generation system, as well as the ability of smart EVs to shift demand and provide PFR, are based on the results in [12]. In this section, the study is carried out over GB 2030 Green World scenario [13], including the generation capacities and demand profiles. Three cases are studied, which are Inflexible EV, Flexible EV without PFR and Flexible EV with PFR. The assumptions in each case are presented in Table I. The annual system operation cost, wind curtailment and emission are calculated based on the simulated system operations for these cases, and the benefits for the Flexible EV cases are quantified against the Inflexible EV case.

Table I. Assumptions on the flexibility of EVs

	Inflexible EV	Flexible EV without PFR	Flexible EV with PFR
Maximum % of EVs load could be shifted	0	80%	80%
Maximum % of EVs load could provide PFR	0	0	50%

The results in Figure 5 show that flexible EVs could reduce the annual system operation cost by about 350M£, while the capability to support PFR could potentially further reduce the operation cost by 300M£. Similarly, as shown in Figure 6, wind curtailment and carbon emission could be reduced by 8% and 4.5%

respectively, if flexible EVs are deployed. These benefits could be doubled if PFR support from EVs is also enabled. In the case of Flexible EVs with PFR, 2.44 GW of PFR is scheduled on average for each hour, 0.93 GW of which is supplied by EVs. Most of present research only focuses on the capability of EVs in performing demand shifting. While this analysis clearly demonstrates that PFR provision from EVs could deliver similar level of benefits as demand shifting capability from EVs and therefore the research on the PFR provision from EVs should be enhanced.

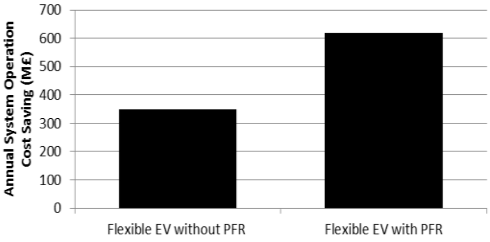

Figure 5 Annual operation cost saving

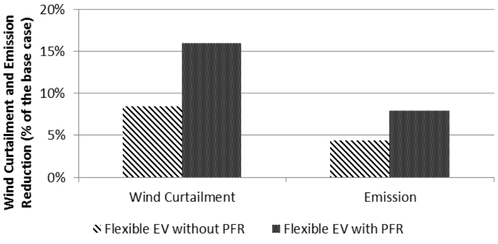

Figure 6 Wind curtailment and emission reduction

4. Conclusion and Future Work

This paper implements an advanced stochastic scheduling model to first analyze the challenges on PFC in the future GB electricity system. The required volume and the associated cost of PFR would be significantly increased, driven by the limited inertia capability of wind plants. The second part of the paper demonstrates that PFR provision of EVs could significantly reduce system operation cost, wind curtailment as well as carbon emissions. PFR provision from EVs could deliver similar level of benefits as demand shifting capability from EVs. Next step, the benefits of PFR provision of EVs should be further analyzed under different charging strategies. The capability of fast delivery of PFR from EVs also requires further investigation.

Acknowledgements

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Reference

[1] J. O'Sullivan, A. Rogers, D. Flynn, P. Smith and M. O'Malley, "Studying the Maximum Instantaneous Non-Synchronous Generation in an Island System—Frequency Stability Challenges in Ireland," *IEEE Trans. Power Syst.,* vol. 29, no. 6, pp. 2943 - 2951, 2014.

[2] V. Gevorgian, Y. Zhang and E. Ela, "Investigating the Impacts of Wind Generation Participation in Interconnection Frequency Response," *IEEE Trans. Sustain. Energy,* p. Accepted, 2014.

[3] National Grid frequency fesponse working group, "Frequency Response report," 2013.

[4] F. Teng, M. Aunedi, D. Pudjianto and G. Strbac, "Benefits of demand-side response in providing frequency response service in the future GB power system," *Front. Energy Res,* vol. 3, no. 36, 2015.

[5] Y. Mu, J. Wu, J. Ekanayake, N. Jenkins and H. Jia, "Primary Frequency Response From Electric Vehicles in the Great Britain Power System," *IEEE Trans. Smart Grid,* vol. 4, no. 2, pp. 1142 - 1150, 2013.

[6] J. Zhon, L. He, C. Li, Y. Cao, J. Wang, B. Fang, L. Zeng and G. Xiao, "Coordinated control for

large-scale EV charging facilities and energy storage devices participating in frequency regulation," *Applied Energy,* vol. 14, p. 253 – 262, 2014.

[7] I. Pavic, T. Capuder and L. Kuzle, "Value of flexible electric vehicles in providing spinning reserve services," *Applied Energy,* vol. 157, pp. 60 - 74, 2015.

[8] National Grid, "Security and Quality of Supply Standards," [Online]. Available: http://www2.nationalgrid.com/UK/Industry-information/Electricity-codes/System-Security-and-Quality-of-Supply-Standards/.

[9] F. Teng, V. Trovato and G. Strbac, "Stochastic Scheduling with Inertia-dependent Fast Frequency Response Requirements," *IEEE Trans. Power Syst.*, 2015, In Press.

[10] F. Teng and G. Strbac, "Assessment of the Role and the Value of Frequency Response Support from Wind Plants," *IEEE Trans on Sustain. Energy,* 2015, In press.

[11] P. R. Almeida, F. Soares and J. P. Lopes, "Electric vehicles contribution for frequency control with inertial emulation," *Electric Power Systems Research,* vol. 127, pp. 141 - 150, 2015.

[12] M. Aunedi, M. Woolf, G. Strbac, O. Babalola and M. Clark, "Characteristic demand profiles of residential and commercial EV users and opportunities for smart charging," in *CIRED*, Lyon, 2015.

[13] Poyry, "Synergies and conflicts in the use of DSR for national and local issues," UK Power Networks, London, 2014.