RELIABILITY AND ECONOMIC IMPLICATIONS OF COLLABORATIVE DISTRIBUTED RESOURCES

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ABSTRACT

Large-scale penetration of distributed energy resources such as Wind Farms (WF) and Electrical Energy Storage (EES) will be key attributes of future distribution networks. In this light, it is essential to develop a comprehensive understanding of how these resources actively affect reliability levels and distribution network reinforcement needs. In this work, WF and EES contribute to network reliability by providing capacity during post-fault operations, thus deferring reinforcement needs that are triggered by load growth. A reliability assessment framework based on Sequential Monte Carlo simulation is used to quantify the reliability improvements owing to WF and EES. To this end, the classic concept of Effective Load Carrying Capability is used to calculate their capacity contribution. Furthermore, the economic benefit for the DSO associated with the resources' capacity credit is also calculated. The methodology is demonstrated using a real UK 11kV distribution network.

INTRODUCTION

The electricity network is increasingly being characterized by a massive penetration of renewables [1] and novel Information and Communication Technologies (ICT) [2]. On the one hand, the large volume of variable renewables (e.g., wind) is challenging, and will continue to challenge, the operation and reliability of electricity distribution networks [3]-[4]. On the other hand, ICT can facilitate the commercial and operational interaction between different actors including, for example, Distribution System Operators (DSOs), Wind Farms (WF) and Electrical Energy Storage (EES) [5]. For instance, EES could coordinate with WF to tackle the intermittency of wind power output [6].

Existing literature on reliability assessment of WF and EES [7]-[9] requires the use of probabilistic approaches (e.g., state-enumeration [9]), among which SMCS is preferred when managing multiple sources of uncertainty, particularly when modelling the sequence of events is critical (e.g., for post-fault restoration sequence modelling). However, existing work [7] [8] tends to focus on generation adequacy, economic implications and/or smart operation (e.g., islanding) without explicitly modelling the network conditions, thus neglecting network voltage and thermal limits which are critical for distribution network analysis.

On the above premises, a methodology based on SMCS is proposed for the assessment of reliability while explicitly quantifying network impacts associated with different operational strategies (i.e., independent or collaborative operation of WF and EES) via the capacity credit concept. More specifically, full post-fault restoration processes are simulated while capturing the significant variability of wind and load profiles and randomly located network faults. The classic concept of Effective Load Carrying Capability (ELCC) [7] is used to indicate the resources' capacity credit, within the context of potential load growth. The capacity credit is used to quantify increased distribution network capacity to be gained from different post-fault operational strategies for WF and EES. The economic benefits associated with this additional network capacity is quantified based on the cost benefit analysis framework used by UK DSOs and relevant network reinforcement planning practices[8][9]. In particular, this work provides a holistic techno-economic analysis of coordinating the operation of WF and EES in the context of future smart grids with significant ICT enabled automated infrastructure. To this end, it is firstly assumed that WF and EES operate independently, which limits the flexibility of EES to cope with WF fluctuations. Thereafter, assuming the aforementioned ICT infrastructure is in place, WF and EES collaborate to maximize network capacity support during Post-fault Operations. This collaborative operation could be offered to DSOs which, after paying a fee, could benefit from increased network reliability levels and/or postponed (even withdrawn) investments in distribution network upgrades. The proposed approach is demonstrated on a real UK distribution network.

COLLABORATIVE OPERATION OF WF-EES

The capability of WF and EES to provide capacity is limited by their own physical limitations (e.g., the intermittency of WF and the energy capacity of EES). In this work, a strategy is proposed to maximise the capacity contribution from WF and EES. More specifically, it is considered that EES owners would have access to load consumption and wind power output forecasts during the post-fault event (see Fig. 1).

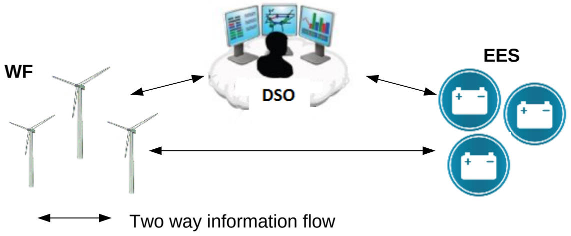

Fig. 1: Interactions between actors for the collaborative WF-EES

This would allow scheduling EES to fill the gaps between the wind generation and load consumption, so that the post-fault capacity support provided by WF and EES would be maximised.

ECONOMIC ASSESSMENT

The post-fault capacity provided by the coordinated operation of WP and EES can effectively increase distribution network capacity. This additional capacity can defer (or withdraw) costly network reinforcements required due to load growth. In order to quantify the relevant economic benefits for DSOs, a distribution network reinforcement planning engine based on the existing business model for UK DSOs, real network costs and load growth forecast for the relevant network (produced by the relevant DSO) were used. Further details on the engine and input data are beyond the scope of this work and not included due to space limitations. However, more details can be found in [9].

RELIABILITY ASSESSMENT WITH SMCS

The use of SMCS presented here allows proper modelling of the sequence of restoration actions, auto-correlated wind profiles and EES charging. This is critical for a realistic assessment of reliability in the face of inter-temporal constraints of the aforementioned resources [10].

The full restoration process includes isolation, switching, and repair and corrective actions taken by the DSO (see [11] for more details for the SMCS framework developed). For every sample year, random time to failure/repair and switch are generated for the components using exponential distribution functions. The simulation platform uses Matpower [12] for a full yearly AC power flow of hourly resolution. Finally, reliability indices such as Customer Interruptions (*CI*), Customer Minutes Lost (*CML*) and Expected Energy Not Supplied (*EENS*) are calculated according to [13].

ELCC EVALUATION

The capacity contribution of WF and EES is calculated based on the concept of ELCC [14]. Accordingly, the capacity contribution of a resource (or aggregated resources) is calculated as the additional load that could be supplied by the network while preserving the original reliability level. The original network is the network before the integration of the resources. The reliability level here is represented by the *EENS*[14].

CASE STUDY

In this section, the proposed methodology is demonstrated on a real UK 11kV distribution network. The network comprises two radial feeders, interconnected through a normally open point, which supplies mostly residential and commercial customers (modelled as Profile Class 1 and 4 [15]). Currently, the network is oversized and there is no need for network capacity. Therefore, for the sake of illustrating the proposed approach under realistic conditions, demand has been scaled up (i.e., 9.51 MW peak) without compromising the reliability targets of the UK regulator (i.e., Ofgem) [16].

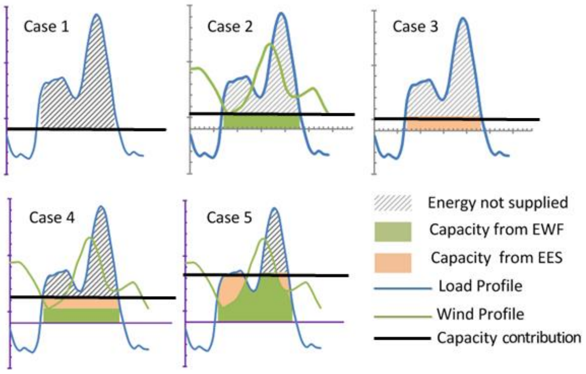

Fig. 2: Cases for the operational strategies

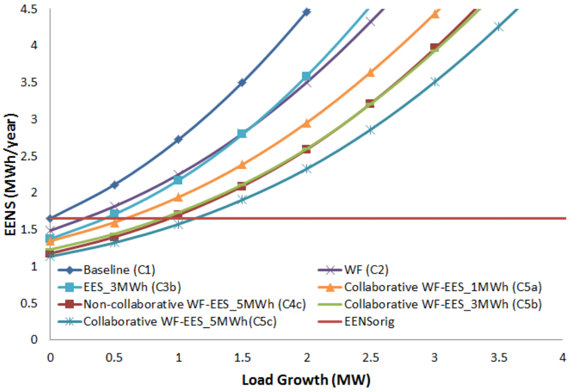

Fig. 3: Impact of load growth on EENS for all the scenarios.

As suggested by the relevant DSO [17], a failure rate of 0.1778/km was used for feeder 1 and 0.1543/km for feeder 2, and fast automatic switching operations (i.e., within three minutes) are considered. However, it is important to note that the approach is flexible enough to consider other alternatives (see e.g. [18]).

It is considered that WF and EES are called to provide capacity support during post-fault operations. However, load curtailment would also be initiated by the DSO if the additional capacity provided by WF and EES is not enough to maintain voltages and currents within limits. Hence, loss of supply could be attributed directly to either a failure or a corrective curtailment, and consequently deteriorates the reliability level (reliability indicators increase). Besides load curtailment, another corrective action considered is to update the tap ratio of the 11kV/400V transformers in case of voltage violations.

Wind Profiles and Wind Power Output

Hourly wind speed data at the location under study is taken for 33 years [19]. For each sampling year the

SMCS randomly selects an hourly wind profile for a full year (from the 33-year database). The power output of the WF is then estimated using the power curve model presented in [20] and assuming a capacity of 4.6MW (see 'Lowca' WF [21], which can be a representative case for WF at the distribution level).

Electrical Energy Storage

In order to explore the impacts of EES, three different energy capacity levels are considered in the case study, including 1 MWh, 3 MWh and 5 MWh (denoted by subscripts a, b and c respectively). It is assumed that the specific amount of energy is reserved for post-fault operation. Regarding the charging and discharging rate of the storage, this is not explicitly predefined, but it is constrained by the levels of energy stored and discharging duration.

Cases

Five cases for the operation of WF and EES are considered, as discussed in detail below (see Fig. 2.):

- **Case 1 (C1): Baseline**: In this case, there are no resources integrated in the network. Thus, the amount of load that is above the maximum load that the network can supply during post fault operations is curtailed. This would be represented by the reliability level of the original network.

- **Case 2 (C2): WF**: Only a WF is connected to the network in this case. The WF's capacity contribution is determined by the maximum wind output power that constantly lasts throughout the fault period. In other words, this is a capacity that WF guarantees to provide continuously. For instance, if the wind output power was expected to be zero at any time during the fault period, the WF's capacity contribution would be zero as it failed to provide a capacity constantly.

- **Case 3 (C3): EES**: Only EES is connected to the network in this case, whereby the capacity contribution from EES is the maximum discharging power that, similar to WF, lasts throughout the fault period. More specifically, this discharging power is determined by the energy reserved for the fault and the duration of the fault.

- **Case 4 (C4): Non-collaborative WF-EES**: WF and EES provide capacity support independently (for instance due to the lack of communication between the assets' owners). In this case, the EES would not use its flexibility to dispatch according to the wind fluctuations. The overall available capacity is the sum of the individual ones.

- **Case 5 (C5): Collaborative WF-EES**: In this case EES will be discharged to compensate for wind power variations. More specifically, EES targets to maximise the overall capacity support to the network by filling the gaps between the expected wind power outputs and load consumption during the fault period.

With the assumption that any load in C1 would trigger the need for network reinforcement, it is clearly illustrated in Fig. 2 that the integration of WF and EES enables the network to withstand a certain level of load growth without demanding network reinforcement. This level of load growth will be quantified as the capacity credit of WF and/or EES in line with the concept of ELCC, as mentioned earlier.

Results and discussions

The results of the study (for C1 to C5 with selected levels of EES) for a range of load growth are presented in Fig. 3. Note that the original reliability level is represented with $EENS_{orig}$.

The baseline case C1 is shown for comparison purposes. It can be seen that the introduction of WF (C2) provides a mild reliability improvement (similar performance to $C3_b$). Reliability is further improved when both devices are operated (C4 and C5). However, it can be noted that the collaborative operation performs much better than the non-collaborative one ($C5_c$ better than $C4_c$). Interestingly, it can be seen that when the resources collaborate, a smaller level of storage is required for a similar reliability performance with non-collaborative resources ($C4_c$ performs similarly to $C5_b$). Finally collaborative resources with small storage level perform better than a stand-alone EES of a higher level ($C5_a$ better than $C3_b$)

The premise that collaborative behaviour (C5) outperforms other alternatives is corroborated in terms of *CI* and *CML* with the results presented in Table I.

It is also worth mentioning that $C5_c$ is the only scenario that complies with the Ofgem reliability targets after the corresponding load growth. This implies that the need for network reinforcement can only be withdrawn on condition that the integrated WF and EES operate collaboratively; otherwise, network reinforcement is inevitable though the same amount of WF and EES are in the network.

The capacity credit for the different scenarios in Fig. 3 is presented in Table II. It can be observed that $C5_c$ has the highest ELCC value. Additionally it can be seen that when the resources collaborate they could perform similar to non-collaborative resources with a smaller size of EES ($C5_b$ similar to $C4_c$). The capacity credit of collaborative WF-EES is always higher compared to non-collaborative resources of the same level of EES ($C5_c$ higher than $C4_c$). Additionally it is interesting to observe that collaborative resources of a small level of EES could give a higher capacity credit of a stand-alone EES of a higher size ($C5_a$ higher than $C3_b$).

In order to estimate the economic benefits for DSOs from the additional network capacity provided in each case, the relevant capacity credit is calculated. This information is used to calculate DSO revenues in terms of the Net Present |Value (NPV). The NPV taken as the discounted savings between optimal network reinforcements with and without the additional capacity associated with each case and subject to several realistic load growth scenarios detailed in [9]. The results are presented in Table II.

The results provide further evidence that collaboration between WF and EES can provide attractive capacity

Table II *CML* and *CI* for the different cases

[Ofgem *CML*=55.6] **[Ofgem *CI* =55.2]**	*CML* *(min./year)*	*CI* *(int.100cust/year)*
C1 (Baseline)	118.58	37.50
C2 (WF)	86.37	28.16
C3$_c$ (EES)	86.8	25.35
C4$_c$ (non-coll. WF-EES)	62.68	18.40
C5$_c$ (coll. WF-EES)	52.78	16.32

*For the sake of simplicity, only a specific load growth (2MW) and storage capacity (5 MWh) levels are presented.

Table I ELCC and DSO NPV for different scenarios

Cases		*ELCC (MW)*	*DSO NPV (£x10^3)*
C2	only WF	0.25	115
C3$_b$	EES_3MWh	0.42	192
C5$_a$	Collaborative WF-EES _1MWh	0.58	260
C4$_c$	Non collaborative WF-EES_5MWh	0.94	404
C5$_b$	Collaborative WF-EES_3MWh	0.86	390
C5$_c$	Collaborative WF-EES_5MWh	1.12	428

and economic contributions compared with other alternatives (including non-collaborative behaviour).

CONCLUSIONS

This paper has presented a probabilistic assessment associated with the reliability implications of using distributed energy resources such as WF and EES for post-fault services. The capacity credit associated with those resources has also been evaluated using the well-known ELCC concept. A collaborative operation of those resources has been proposed, and more specifically the optimal scheduling of the EES during the post-fault operation so as to maximize the wind power utilization.

The studies have been developed and performed within a SMCS framework allowing the full use of time series analysis. This approach enables the actual capacity requirements of the considered resources to be properly captured during a random contingency. This information could be important for the DSO in case they would like to evaluate the network capacity needs due to load growth. Furthermore, the capacity credit calculated for WF and EES could be a representative value to encourage services and interactions between DSOs and other actors against DSO infrastructure interventions. Regarding the different operational strategies, it is shown that collaborative resources could provide higher reliability improvements and consequently higher ELCC comparing to a stand-alone resource of non-collaborative ones.

Work in progress aims to understand how the findings relevant to reliability contribution of integrated storage and renewable technologies can be extended to resilience aspects, as well as to consider specifically the role of distributed photovoltaic generation coupled to local energy storage.

ACKNOWLEDGEMENTS

This work was developed with the contribution and within the scope of the EPSRC funded Autonomic Power Systems (APS - ref no. EP/I031650/1), RESNET (ref no. EP/I035757/1), and WISE-PV (ref no. EP/K022229/1) projects, which the authors kindly acknowledge. APS aims to develop innovative control solutions for future grids dominated by distributed autonomous systems; RESNET focus on analysing the impact of climate change on the future GB power system with high penetration of renewable generation; WISE-PV targets to investigate the techno-economic implications of the wide scale integration of photovoltaic systems into future grids with particular emphasis on the UK.

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