Grid Strength Analysis for Integrating 30 GW of Offshore Wind Generation by 2030 in the U.S. Eastern Interconnection

Preprint

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Grid Strength Analysis for Integrating 30 GW of Offshore Wind Generation by 2030 in the U.S. Eastern Interconnection

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Abstract

Offshore wind is a key player in the transition to a decarbonized electric gird, and the United States has set ambitious goals of integrating 30 GW of offshore wind capacity by 2030 and 110 GW by 2050. To facilitate this integration, the National Renewable Energy Laboratory and the Pacific Northwest National Laboratory are conducting the Atlantic Offshore Wind Transmission Study to assess transmission solutions. To achieve the 110-GW target by 2050, meticulous planning for network expansion and resource allocation is essential; however, meeting the 2030 goals requires integrating offshore wind power with minimal system upgrades, thus necessitating a careful study of grid strength and stability. The study team developed the Automated System-wide Strength Evaluation Tool (ASSET) to assess system strength under various operating conditions and contingencies, focusing on the proposed integration of 30 GW of offshore wind power by 2030. In this paper, we provide a summary of key features of the ASSET software and results of the grid strength analysis for integrating 30 GW of offshore wind generation by 2030 in the U.S. Eastern Interconnection.

1. Introduction

The United States has planned to achieve upward of 35% of energy generation through renewable energy resources by 2030 [1]. To reach this target within a short time frame, it is necessary to harness multiple renewable energy resources. Offshore wind power plays a significant role in the renewable energy landscape, offering relatively more reliable and consistent energy production compared to other renewable energy resources [2]; therefore, the United States has set an ambitious goal of reaching 30 GW of offshore wind capacity by 2030 and 110 GW by 2050 [3], [4]. The Eastern Interconnection of the United States, which reaches from the Atlantic Coast to the Rocky Mountains, serves more than 70% of U.S. electric energy demand, with a total generation capacity of more than 700 GW. Most of the 30-GW target for offshore wind generation by 2030 will be integrated along the U.S. Atlantic Coast in the Eastern Interconnection.

The present grid has been designed with a certain geographical distribution of generation resources, which are predominantly synchronous generators. In this system, we aim to integrate a large amount of offshore wind energy resources. Integrating such a substantial amount of new energy resources requires careful and cost-effective planning for network expansion. To achieve the goals for 2050, detailed planning for network expansion and resource allocation is crucial; however, to meet the 2030 goals, there is limited time to implement major network upgrades, and therefore it is critical to ensure the successful integration of offshore wind power while considering the existing grid's constraints. This necessitates a meticulous study of grid strength, system stability, and various extreme scenarios that can arise with such overhauling of the generation portfolio and its geographical distribution.

Grid strength refers to the system's responsiveness to minor disturbances, such as load fluctuations, equipment switches, or variations of renewable generation. Robust grids serve as stable benchmarks for resources, whereas weaker grids can complicate the connection of new equipment, especially inverter-based resources (IBRs). These resources rely on sufficient grid strength to synchronize power electronics. One way to quantify grid strength is to use the short-circuit ratio (SCR) for the IBRs at their point of interconnection (POI) [5]. Although the SCR metric is ideally suited for a single IBR linking to the larger power system, it still serves as a useful preliminary measure in the context of a long-term integration study for offshore wind [6]. One of the key challenges associated with the large-scale integration of renewable energy resources into an existing grid is their overall impact on system strength. Further, system stress conditions can arise in systems even during low load conditions due to the higher percentage of IBRs in the grid; hence, one needs to analyze the system performance for various operating conditions across seasonal and daily variations.

The National Renewable Energy Laboratory (NREL) and the Pacific Northwest National Laboratory (PNNL) have undertaken an Atlantic Offshore Wind Transmission Study (AOWTS) project to facilitate the integration of offshore wind resources [7]. This study aims to evaluate the feasibility, challenges, and solutions for this large-scale offshore wind integration. This paper presents a comprehensive analysis of system strength and contingency studies for the U.S. Eastern Interconnection, focusing on the proposed integration of 30 GW of offshore wind by 2030. To conduct this analysis, we developed software called the Automated System-wide Strength Evaluation Tool (ASSET), which enables the examination and assessment of large-scale systems for multiple system operating conditions and contingencies and their impacts on system strength. In this work, system strength is assessed in terms of the SCR metric. Other system strength metrics can be easily implemented by taking advantage of the modular structure of the ASSET software. Our study demonstrates that when selecting POIs, multiple operating conditions and contingencies must be considered to ensure that the selected POIs are robust enough to host the offshore wind power integration and to secure stable system operation across a wide range of operating conditions. The analysis of multiple operating conditions revealed counterintuitive findings where the system might be more vulnerable during off-peak conditions with high offshore wind injections into the grid. This paper provides a detailed study of the impact of integrating offshore wind power into the existing grid, specifically examining its effect on system strength. Although the analysis focuses on a particular case study, the findings and outcomes have broader relevance for ambitious projects involving bulk renewable energy integration.

The main contributions of this paper are (i) a detailed strategy for obtaining a power flow solution with the inclusion of new generation resources and the redispatch of existing resources, (ii) a scalable automated tool for analyzing grid strength for a large power system with a multitude of operating conditions, and (iii) insights into the grid behavior with large integrations of renewable energy resources for various operating conditions. The rest of the paper is organized as follows: Section 2 details the preparation of the system model with offshore wind integration. Section 3 presents a detailed description of the ASSET software developed for this analysis. Section 4 provides a detailed analysis of the Eastern Interconnection system for grid strength. Section 5 summarizes the learnings of this study and how it can be extended for further research.

2. System Preparation

The Eastern Interconnection, with approximately 700 GW of generation capacity, serves more than 70% of the U.S. electric energy demand. To integrate more than 30 GW of offshore wind resources into the mix, one needs to identify POIs that are economically and technically viable. Further, there is a need to redispatch existing generation units to accommodate the new resources. As shown in Fig. 1, 24 POIs are obtained through a detailed technical and economic analysis by collaborative efforts from industry stakeholders, system operators, and researchers for offshore wind integration. These POIs are geographically dispersed from north to south along the Atlantic Coast, spanning various independent system operators. A detailed discussion on the selection of POIs is not within the scope of this paper. For this paper, we start with the given POIs and the megawatt generation information as a given constraint.

Fig. 1 POIs along the Atlantic Coast in the U.S. Eastern Interconnection for integrating 30 GW of offshore wind generation by 2030.

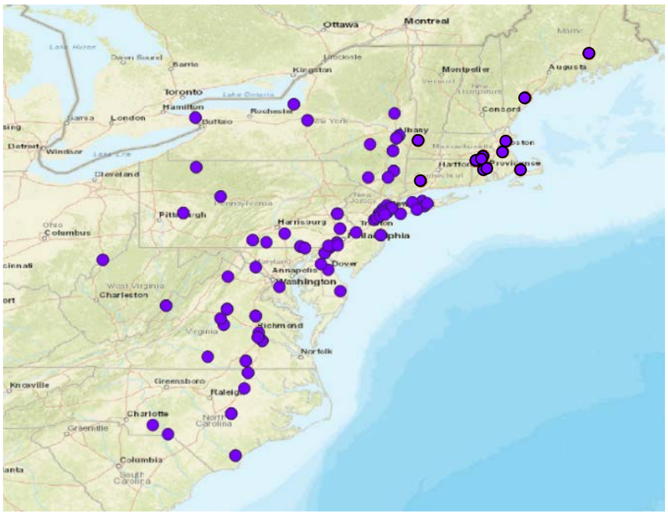


Fig. 2 Units in the U.S. Eastern Interconnection that are redispatched to accommodate 30 GW of offshore wind injection.

To integrate new generation resources, we must reduce and redispatch existing generation resources. In this work, 240 generation units are selected to redispatch and accommodate 30 GW of offshore wind generation injected into the system. Fig. 2 visualizes the selected units for redispatch. The selected units for the redispatch are (i) directly connected to the regional transmission operator market of the corresponding POIs, and are (ii) the peaker gas turbine, steam coal, and gas units, supplemented with combined-cycle units as needed.

To achieve a viable power flow solution for the established system, we developed an automated algorithm that serves the purpose of orchestrating a step-by-step adjustment in the output of various generation units to achieve redispatch. The primary objective of this algorithm is to steer the system toward a state of convergence, where all equations governing power flows are satisfied. The flowchart of this algorithm, called the Offshore Wind Integration Tool (OSWIT), is discussed in the following subsection.

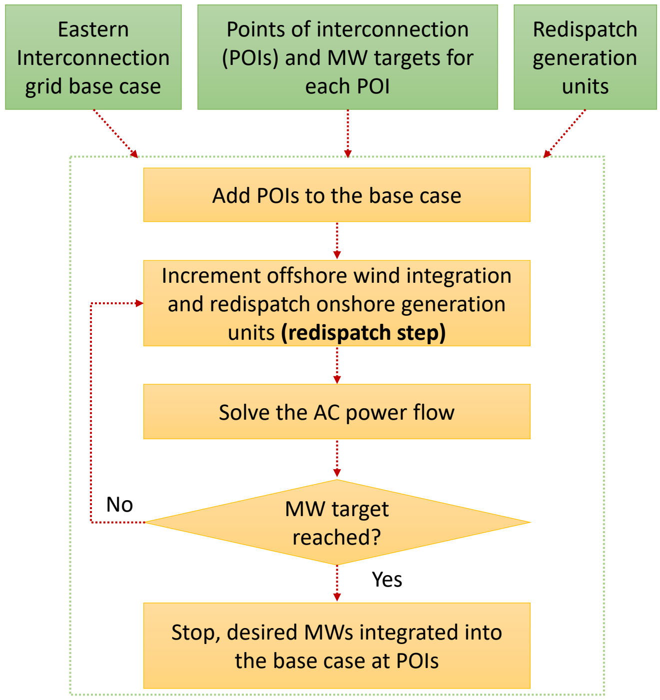


Fig. 3 Flowchart for overall methodology of base case preparation with offshore wind.

2.1 Offshore Wind Integration Tool (OSWIT)

To perform the offshore wind integration, it is crucial to obtain a converged AC power flow base case that appropriately accommodates the desired amount of offshore wind generation. To develop the base power flow cases with 30 GW of offshore wind generation, given the scale of the problem, we developed a fully automated algorithm, called the Offshore Wind Integration Tool (OSWIT). OSWIT requires the following inputs:

- An AC power flow base case without offshore wind. The selected base case spanning the entire Eastern Interconnection is identified as the 2031 Multiregional Modeling Working Group (MMWG) base case [8].
- Generators that need to be redispatched to accommodate the integration of 30 GW of offshore wind generation.
- The POI locations where the offshore wind is added and their respective wind injection volume in megawatts.

Informed with this, we implemented an iterative algorithm that incrementally increases the offshore wind at the POIs while simultaneously decreasing the same amount of power injection from the generators that will be redispatched so that the total load and generation in the system remain approximately balanced. After redispatching the units, the AC power flow is solved, and a check for the total offshore megawatt target is performed, as illustrated in Fig. 3. If the total offshore megawatt target is reached, then the process exits; otherwise, the process continues. Further, to analyze the seasonal variability of the load and generation and extreme conditions, we have considered two additional scenarios around the base case: a peak load condition during the summer months (referred as SUM) and a peak load condition during the winter months (referred to as WIN). We also considered a scenario with low load and high IBR integration—namely, the spring weather low demand condition to analyze the impact of a higher percentage of IBRs in the total generation. The obtained scenarios for the wind integration act as the foundation for all further studies to analyze system strength.

Table 1 Summary of offshore wind scenarios considered for the study.

Case Name	Description
MMWG_SUM	Summer peak load case without offshore wind
MMWG_WIN	Winter peak load case without offshore wind
OSW_SUM_redispatch	Summer peak load case with offshore wind
OSW_WIN_redispatch	Winter peak load case with offshore wind
OSW_SUM_redispatch_status	Summer peak load case with offshore wind with optimal redispatch
OSW_WIN_redispatch_status	Winter peak load case with offshore wind with optimal redispatch
OSW_SPR_redispatch	Spring low demand case with higher percentage of offshore wind in the total generation

3. Grid Strength Analysis Approach

3.1 Description of Grid Strength Analysis Method

The proposed grid strength analysis is based on the SCR. SCR is a metric traditionally used to represent the bus voltage stiffness in a grid. The SCR metric is well-defined and can be uniquely calculated for power grids with a single POI of IBRs. In this case, the SCR is the ratio between the short-circuit MVA at this POI and the total megawatt capacity of the connected IBR. If the SCR is higher, then there is a stronger grid condition at this POI such that the grid is more capable of withstanding and recovering from short circuits or faults. In contrast, a lower system strength condition implies that the connected IBRs, particularly with grid-following controls, might be more likely to exacerbate perturbations and disturbances, resulting in oscillatory instabilities and/or maloperation of protection relays [9]. In general, there is no unique, clear threshold for SCR to distinguish a weak grid condition from a strong grid condition. A general rule of thumb is to classify a grid to be weak if SCR <3 and strong if SCR >5 [10]. Note that SCR <3 does not necessarily mean system instability; a power grid having several POIs with SCR <3 can still be stable. Still, thanks to its simplicity, SCR can be used as a screening tool to identify the most vulnerable locations in a grid. A low SCR indicates that more detailed studies, such as electromagnetic transient simulations and frequency scan analysis [11], [12], would be needed to further investigate the system dynamic performance. In this paper, although we use only the SCR metric in the developed software to assess grid strength, other system strength metrics, such as the impedance metric [13], can be added by taking advantage of the modular structure of the software.

3.2 Automated System-wide Strength Evaluation Tool (ASSET)

ASSET, illustrated in Fig. 4, is developed to enable the examination and assessment of large-scale systems for multiple system operating conditions under credible contingencies and their impact on system strength. ASSET is developed in Python leveraging the PSS/E Python application programming interface for calculating the short-circuit current (SCC) at different nodes. The flowchart of the tool is shown in Fig. 5. More details about the tool and its key steps are described next.

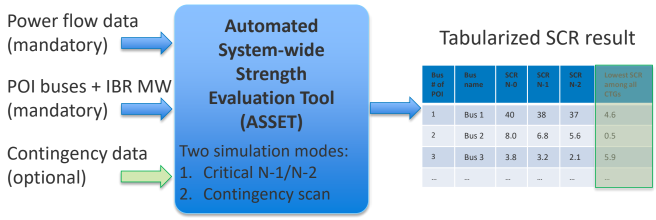


Fig. 4 ASSET software.

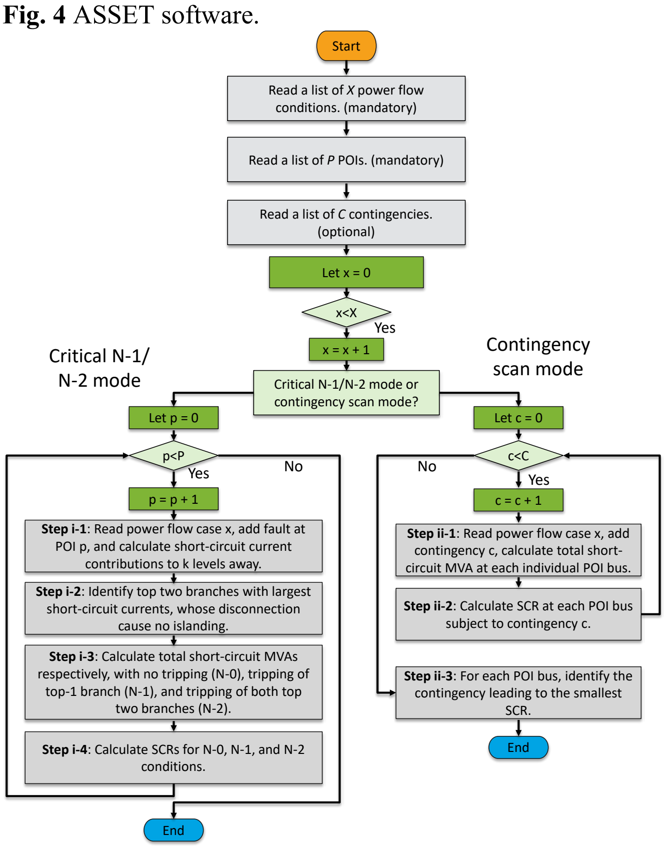


Fig. 5 Flowchart of the ASSET software.

Input files: ASSET requires two types of mandatory input files and one optional input file. The mandatory input files include the power flow data file(s) and the POI data file. Each power flow data file represents a different loading/dispatch condition. The power flow does not need to be solved because the SCC calculation does not require a converged power flow case. The POI data file contains a list of POI buses and the total megawatt capacity of the connected IBRs for each POI bus. The optional input file contains the list of contingencies, which is required when the contingency scan mode is selected in ASSET.

Simulation mode: ASSET has two simulation modes: the critical N-1/N-2 mode and the contingency scan mode. For each POI bus, the critical N-1/N-2 mode aims to identify the top two branches whose disconnections will cause the largest reductions in system strength without leading to an islanding condition at the POI. Fig. 6 gives an example of identifying the top two branches, where the fault is added to bus 7, and the largest SCC occurs on line 6-7; however, disconnecting line 6-7 causes an islanding condition at bus 7, so line 6-7 is skipped to avoid an islanding condition, and lines 2-4 and 4-6 are identified as the most critical contingencies for system strength. Once the top two branches carrying the largest SCCs are identified, ASSET will calculate the SCR for N-0 and the critical N-1 and N-2 conditions. Note that the critical branches identified by ASSET can be different from those used for the real-time contingency analysis applied in the North American Electric Reliability Corporation Standard TOP-001-3 [14]. The contingency scan mode calculates the SCR at each POI under each contingency defined in the optional input file with a list of contingencies; this could further identify the most critical contingency from the list that causes the largest reduction in system strength. Note that each POI bus could have a different critical contingency.

Short-circuit calculation: The International Electrotechnical Commission Standard 60909-0:2016 is adopted to calculate the SCCs and short-circuit MVA in PSS/E [15]. Default PSS/E settings are used. In addition, the three-phase fault is applied, and the initial symmetrical SCC, I_k'', is used to facilitate the calculation of the SCR. To identify the top two critical branches, I_k'' contributions over the network are observed up to k buses away from the fault at the POI bus. k is kept 10 in all numerical studies presented in this paper.

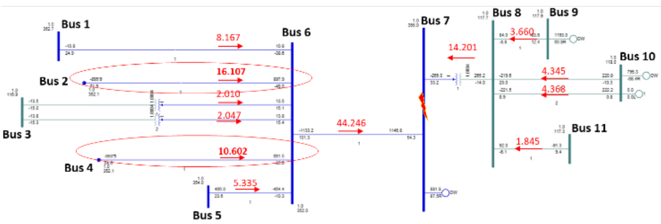


Fig. 6 Example of SCCs on the network and top two branches carrying the largest SCCs.

3.3 ASSET Graphic User Interface

This section introduces the ASSET graphical user interface (GUI). Fig. 7 shows the ASSET GUI; most of the components shown here were covered in Section 3.2 except for the configuration file. This contains the parameters and their values used for configuring the grid strength analysis simulation, e.g., short-circuit analysis settings, input format, and output format. Also, there is a selection button to include fault current contributions from other IBR units. When the radio button “No” is checked, the fault current contributions from IBRs other than the POI bus under study are disabled by assigning a very large source impedance, e.g., 9999.0 p.u. as the default value used by ASSET, to all IBRs. Otherwise, if “Yes” is checked, then only the IBR(s) connected to the POI bus under evaluation will be assigned a large source impedance.

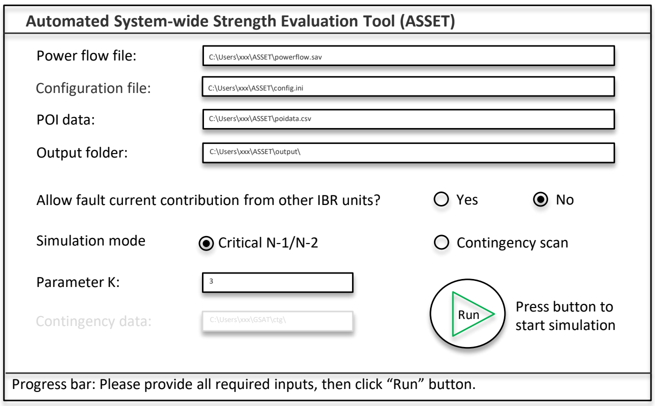


Fig. 7 ASSET GUI

3.4 ASSET Example on a 23-Bus System

This subsection demonstrates how to apply ASSET to analyze the grid strength on a 23-bus test case at prespecified buses. This is a built-in example in PSSE, which we consider for the integration of IBRs. With the critical N-1/N-2 mode selected, the power flow file of the 23-bus case and the following POI data file in Table 2 are provided to ASSET. For this study, we assume that the fault current contributions from other IBR units are not allowed. Parameter k is kept as 10.

Table 2 POI data for IBR-based injection in 23-bus system.

POI bus #	IBR ID	IBR MW capacity
151	OW	100
152	OW	100
153	OW	100
154	OW	100
201	OW	100
202	OW	100
203	OW	100
3011	OW	100

Table 3 Contingency data

CTG #	Events
1	Disconnect bus 3004
2	Trip line 151-152 (ID=2)
3	Trip line 152-153 (ID=1)
4	Trip generator 101 (ID=1)
5	Trip generator 3011 (ID=1)

Table 4 Identified critical N-1/N-2 branches

POI bus #	Most critical branch			2nd most critical branch		
	From Bus	To Bus	ID	From Bus	To Bus	ID
151	151	201	1	152	153	1
152	152	153	1	154	205	1
153	152	153	1	154	205	1
154	154	205	1	152	153	1
201	151	201	1	204	205	1
202	202	203	1	152	202	1
203	202	203	1	154	203	1
3011	3001	3003	1	154	205	1

Table 5 Short-circuit MVA results

POI bus #	SCMVA N-0	SCMVA N-1	SCMVA N-2
151	7915	6535	6303
152	6382	5631	5550
153	5862	3447	2541
154	6357	3992	3157
201	6901	4835	3960
202	5811	5048	2567
203	4955	3476	2731
3011	4577	3812	3779

Table 6 SCR results for 23-bus system

POI bus #	SCR N-0	SCR N-1	SCR N-2
151	79.15	65.35	63.03
152	63.82	56.31	55.50
153	58.62	34.47	25.41
154	63.57	39.92	31.57
201	69.01	48.35	39.60
202	58.11	50.48	25.67
203	49.55	34.76	27.31
3011	45.77	38.12	37.79

Table 7 SCMVA (top) and SCR (bottom) results under contingencies

POI bus #	N-0	CTG #1	CTG #2	CTG #3	CTG #4	CTG #5
151	7915	7733	7595	7709	5749	7368
	79.15	77.33	75.95	77.09	57.49	73.68
152	6382	5947	5782	5632	5597	5392
	63.82	59.47	57.82	56.32	55.97	53.92
153	5862	5664	5450	3448	5269	4961
	58.62	56.64	54.50	34.48	52.69	49.61
154	6357	6271	6173	5964	5863	5570
	63.57	62.71	61.73	59.64	58.63	55.70
201	6901	6770	6901	6840	5899	6400
	69.01	67.70	69.01	68.40	58.99	64.00
202	5811	5598	5572	5621	5189	5141
	58.11	55.98	55.72	56.21	51.89	51.41
203	4956	4873	4825	4953	4588	4487
	49.56	48.73	48.25	49.53	45.88	44.87

After executing the analysis, ASSET creates three output files: (i) critical N-1/N-2 branches, (ii) short-circuit MVAs, and (iii) SCRs, respectively, shown in tables 4–6. Note that the SCRs in Table 6 are all very high. This is mainly due to the fictitious IBR megawatt capacity data in Table 2 and the fact that the 23-bus system is a strong grid.

When the contingency scan mode is enabled, ASSET would further require the contingency data file. An example contingency data file is shown in Table 3. After running the contingency scan analysis in ASSET, one output file will be created containing the SCR results at each POI bus under each contingency, as shown in Table 7.

4. Grid Strength of Eastern Interconnection

This section presents the grid strength analysis results of the 24 candidate POI buses in the 2031 MMWG base cases using ASSET. As introduced in Section 2, we have two base cases: a summer case (SUM) and a winter case (WIN). Starting from each of the two base cases, we create two more cases: One is to add 30 GW of offshore wind generation at the 24 POIs while redispatching the existing generators to reach the balance between system generation and load, named *OSW_Redispatch*, as discussed in Section 2. The second case further turns off the selected generators with low output along with additional generation redispatches, named *OSW_Redispatch_Status*. This results in a total of six power flow cases. For each of the six cases, we apply ASSET to identify the top two most critical branches, and we calculate the SCRs under N-0, N-1, and N-2 conditions, respectively, at the 24 POI buses. Detailed results are summarized in Table 8 and Table 9.

Following are a few remarks on the grid strength analysis results shown in Table 8 for the 2031 MMWG SUM case:

- Under an N-0 condition, most POIs have high SCRs, i.e., greater than 3.0 and up to 40.0, with only the POI for bus 24 having an SCR less than 3.0.
- Under an N-1 condition, there are five POI buses with SCRs less than 3.0.
- Under an N-2 condition, there are 11 POI buses with SCRs less than 3.0, which are geographically dispersed.
- For each POI bus and for each case, it is expected that the SCR decreases when more lines are tripped. It is interesting that the SCRs at some buses decrease quickly, such as POI bus 6 in the base case, whose SCR decreases from 10.8→5.8→1.4, whereas the SCRs at some other buses decreases relatively slowly, such as POI bus 21, whose SCR decreases from 3.4→2.7→2.6, as shown in Table 8. Therefore, a high SCR under an N-0 condition does not imply a high SCR under N-1/N-2 conditions. Also, a relatively low SCR under an N-0 condition does not indicate a significantly worse SCR under N-1/N-2 conditions.
- Comparing *OSW_Redispatch* (middle three columns) to the base case (left three columns)shows, not surprisingly, that (i) buses with low (or high) SCRs in the base case also have low (or high) SCRs with 30 GW of offshore wind, and (ii) adding offshore wind and redispatching existing generators without turning them off will not significantly reduce the grid strength because all traditional generators are still in service to support SCC and grid strength.
- When going from the middle three columns to the right three, i.e., turning off the selected traditional generators, the largest percentages of the SCR reductions occur at POIs whose SCRs are already very large, e.g., 8–20. This means that no new weak grid conditions are created by turning off the selected traditional generators. This is mainly because the Eastern Interconnection is too big to show a significant impact on SCR reduction when integrating 30 GW of offshore wind. Perhaps the impact will be more severe for the 2050 scenarios being considered in the AOWTS study, which will include an additional ~80 GW of offshore wind generation.

Table 8 SCR results for 2031 MMWG SUM case

Summer									
Bus #	Base-Case			OSW_Redispatch			OSW_Redispatch_Status		
POI	SCR(N-0)	SCR(N-1)	SCR(N-2)	SCR(N-0)	SCR(N-1)	SCR(N-2)	SCR(N-0)	SCR(N-1)	SCR(N-2)
1	3.1	2.2	1.9	3.1	2.2	1.9	3.1	2.2	1.9
2	11.0	9.4	2.4	12.1	10.2	2.4	12.0	9.5	8.5
3	9.3	7.4	5.6	10.6	7.8	5.8	10.5	7.6	5.7
4	10.9	6.2	2.1	11.0	6.2	2.1	10.8	6.2	2.1
5	5.1	5.0	4.2	5.2	5.1	4.3	5.0	4.9	4.1
6	10.8	5.8	1.4	10.9	5.8	1.4	10.5	5.7	1.4
7	40.0	37.9	37.7	39.5	37.2	13.8	36.6	34.8	13.6
8	23.1	20.7	5.4	23.0	20.6	5.4	21.4	19.4	5.4
9	26.2	25.8	20.3	26.0	25.7	20.4	23.8	23.5	19.6
10	26.2	25.8	25.8	26.0	25.7	18.6	23.8	23.5	18.5
11	8.0	6.8	5.6	8.0	6.9	5.6	8.0	6.9	5.6
12	8.4	7.4	3.7	8.2	7.3	3.7	7.6	6.7	3.2
13	9.6	7.6	7.5	9.6	7.6	7.5	8.5	6.9	6.7
14	8.9	5.8	5.8	8.9	5.8	5.8	8.8	5.7	5.7
15	4.7	1.5	1.5	4.7	1.5	1.5	4.6	1.5	1.5
16	9.8	8.4	7.8	10.0	8.5	6.8	9.2	7.9	7.2
17	10.9	9.3	8.8	11.0	9.4	8.9	9.8	8.2	7.8
18	7.8	6.3	2.1	7.8	6.3	2.1	7.4	6.1	2.1
19	4.3	3.1	2.2	4.3	3.1	2.2	4.3	3.1	2.1
20	8.1	6.8	5.7	8.1	6.8	5.7	8.1	6.8	5.7
21	3.4	2.7	2.6	3.4	2.7	2.6	3.3	2.7	2.6
22	3.3	2.5	1.5	3.3	2.5	1.5	2.6	1.8	0.7
23	3.8	3.2	2.1	3.8	3.3	2.1	3.8	3.2	2.1
24	2.5	1.0	1.0	2.5	1.0	1.0	2.5	1.0	1.0

Strong

Weak

Table 9 SCR results for 2031 MMWG WIN case

Winter									
Bus #	Base-Case			OSW_Redispatch			OSW_Redispatch_Status		
POI	SCR(N-0)	SCR(N-1)	SCR(N-2)	SCR(N-0)	SCR(N-1)	SCR(N-2)	SCR(N-0)	SCR(N-1)	SCR(N-2)
1	3.1	2.2	1.9	3.1	2.2	1.9	3.1	2.2	1.9
2	11.0	9.4	2.4	11.1	9.5	2.4	10.9	9.3	2.4
3	9.3	7.4	5.6	9.5	7.5	5.7	9.2	7.4	5.5
4	10.7	6.1	2.0	10.7	6.1	2.0	10.6	6.1	2.0
5	5.2	5.1	4.2	5.3	5.2	4.4	5.1	5.1	4.3
6	10.7	5.7	1.3	10.7	5.7	1.3	10.6	5.7	1.3
7	19.9	19.0	11.3	19.6	18.7	11.1	18.7	17.9	10.7
8	24.7	23.4	17.2	24.6	23.3	17.0	22.0	21.0	16.0
9	26.1	25.7	23.4	26.0	25.6	23.3	23.0	22.6	20.6
10	26.1	25.7	23.4	26.0	25.6	23.3	23.0	22.6	20.6
11	6.6	5.5	4.4	6.6	5.4	4.4	5.2	4.0	3.1
12	6.9	6.2	3.3	6.8	6.2	3.3	6.1	5.5	2.8
13	7.3	6.2	6.1	7.4	6.3	6.1	6.1	5.3	5.1
14	7.4	5.3	5.3	7.5	5.3	5.3	7.3	5.2	5.2
15	4.6	1.5	1.5	4.6	1.5	1.5	4.5	1.5	1.5
16	9.3	7.9	7.3	9.3	8.0	7.4	8.6	7.5	6.8
17	10.3	8.8	8.3	10.4	8.9	8.4	9.2	7.7	7.2
18	7.5	6.1	2.0	7.5	6.1	2.0	7.1	5.8	1.9
19	4.0	2.9	2.0	4.1	2.9	2.0	4.0	2.9	2.0
20	7.2	6.3	3.4	7.2	6.3	3.4	7.2	6.2	3.4
21	3.4	2.8	2.6	3.4	2.8	2.6	3.4	2.8	2.6
22	3.3	2.5	1.5	3.3	2.5	1.5	2.6	1.8	0.7
23	3.8	3.2	2.0	3.8	3.2	2.0	3.7	3.2	2.0
24	2.5	1.0	1.0	2.5	1.0	1.0	2.4	1.0	1.0

Strong

Weak

The SCR results for the winter case are shown in Table 9. The observations basically align with those for the summer case. Table 10 compares the SUM and WIN cases in terms of the number of POI buses with SCR <3.0, which confirms the alignment.

Table 10 Number of POI buses with SCR <3.0

# of POI buses with SCR <3.0	Base Case (SCR)			OSW_Redispatch (SCR)			OSW_Redispatch_Status (SCR)		
	N-0	N-1	N-2	N-0	N-1	N-2	N-0	N-1	N-2
SUM case	1	5	11	1	5	11	2	5	10
WIN case	1	6	11	1	6	11	2	6	12

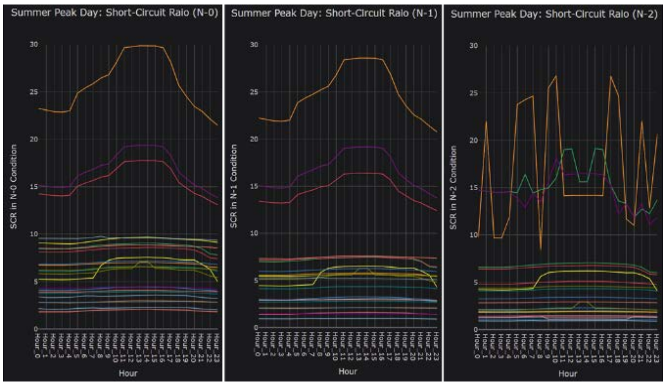
Table 10 shows only the grid strength analysis on two typical power flow conditions. To achieve a broader understanding of system strength throughout a more diverse set of operating conditions, we ran production cost model to determine the generation dispatch for each hour of three typical days: a summer peak day, a winter peak day, and a spring off-peak day. The SCR variations at the 24 POI buses during these 72 hours are shown in Fig. 8. Large variations can be observed at POIs having high SCRs, whereas small variations can be observed at some POIs with low SCRs. Detailed dynamic studies should be performed at low SCR POI buses to ensure satisfactory IBR behavior during grid disturbances and fault events.

In addition, we applied ASSET to analyze the confidential contingency data shared by ISO New England. For each of the 24 POI buses and each contingency, we calculated the SCC and SCR. On a regular laptop computer, it takes approximately 2 hours to complete the scan of one MMWG power flow case. This computational cost is acceptable for the planning study but expensive for an online application in operation.

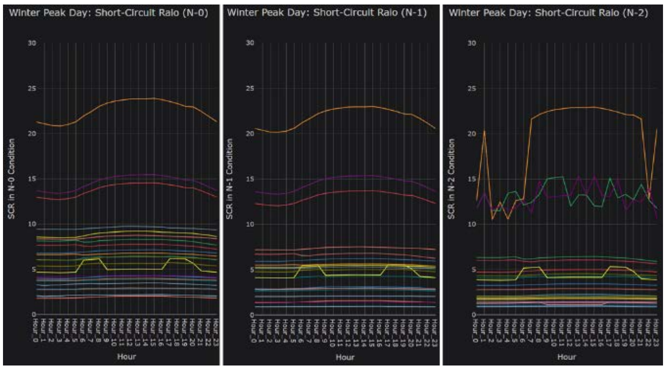
5. Conclusion

In this paper, we analyzed the integration of 30 GW of offshore wind into the U.S. Eastern Interconnection along the Atlantic Coast. This study focused on developing redispatch scenarios for the existing generation portfolio to accommodate offshore wind integration. Following this, we performed a detailed analysis of system strength in terms of SCR for the connected offshore wind resources at their POIs. This detailed analysis highlights the critical POIs and thus provides a roadmap for a detailed study of system dynamics corresponding to these POIs.

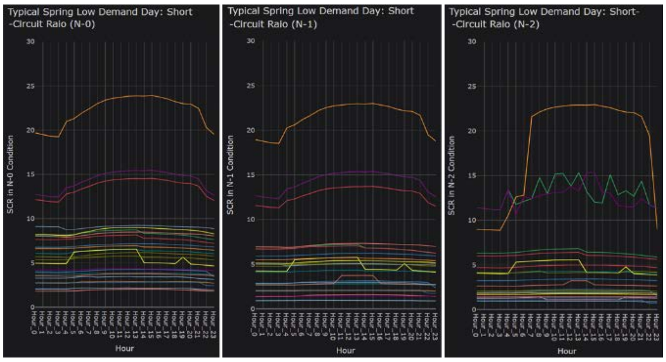
In this process, we developed a scalable automated tool (OSWIT) to redispatch existing generators to obtain a viable power flow solution. Further, we also developed an automated modular tool for system-wide strength analysis (ASSET) that analyzes system strength in terms of SCRs at the POIs of the connected renewable energy resources. Although we analyzed the Eastern Interconnection system in detail, the tools developed in this process can be used for various other studies considering high integration levels of renewable generation in the existing grid.



(a) A typical summer peak day



(b) A typical winter peak day



(c) A typical spring low demand day

Fig. 8 SCR variations over three typical days.

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