Transient Stability Analysis for Offshore Wind Power Plant Integration Planning Studies – Part II: Long Term Faults

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***Abstract*—This paper addresses the transient stability (also called large-signal stability) analysis of power systems for offshore wind power plant integration planning studies. In particular, this study develops a comprehensive practical methodology to assess the transient stability of power systems, including rotor angle stability, voltage stability, and frequency response for large scale power systems. This methodology considers variability of the offshore wind power plants as well as the type of any faulted system' components present and is applicable to the study of both short term and long term faults. Part I of this research discussed the short term faults whereas as Part II, the present paper, discusses long term faults. This research considers the integration of offshore wind power plants into existing power systems and demonstrates the utility of this methodology through the examination of the specific case of integrating 1,000 MW of offshore wind power into the FirstEnergy/PJM service territory using a realistic model of 63k-bus test system that represents the U.S. Eastern Interconnection.**

***Index Terms*—Offshore Wind Integration, Power System Planning, Transient Stability**

I. INTRODUCTION

TRANSIENT signal stability analysis of power systems addresses the dynamical behavior of the system following a large disturbance to assess whether or not it reaches a new equilibrium point. The new post-fault equilibrium point may be same the pre-fault equilibrium point or a different equilibrium point [1].

During the last decade, higher penetration of renewable energy sources, including solar panels and wind turbines, in power systems has raised the concern for stability and dynamics of the power grids. This is because of the fact that renewable energy sources are, typically, integrated into the grid through a power electronic interface and this interface decouples them from the grid. Therefore, their insufficiency in contribution to the grid's inertia makes them unattractive due to these stability issues [2].

The objective of this study is to develop a practical methodology for transient stability analysis of power system for planning studies of offshore wind power plant integration projects. This includes the investigation of rotor angle stability, voltage stability, and frequency response.

The contribution of this research is the scalability and practicality of this methodology in, effectively, identifying dynamical issues associated with the integration of offshore wind power plants in a very large scale power systems. Additionally, this methodology determines the relation among (1) transient rotor angle stability, transient voltage stability, and transient frequency stability, (2) type and size of the faulted system' component, and (3) integration, operation, and variability of the offshore wind power plant following all types of faults.

The advantage of this methodology is its ease in implementation with existing practical power systems models which will inherently include the effects of continuous and discontinuous system's elements. Analytical methods, such as the use of energy functions, present limited applicability for large and complex power systems due to their setbacks including system modeling, the functions definition, and their conditions as well as the reliability and accuracy of the methods [3].

To this end, short term and long term faults are investigated under multiple pre-fault operational levels of power generation by the offshore wind power plant. The examined system' components (faulted for transient stability analysis) here are generators, transmission lines and offshore collector system.

This work considers integration of a 1,000 MW offshore wind power plant, operating in Lake Erie, into the FirstEnergy/PJM service territory and uses a simulation model of the U.S. Eastern Interconnection as the test system. Potential geographical locations of offshore plants and relevant points of interconnection (POIs) are identified based on estimation of wind availability by the U.S. Department of Energy's National Renewable Energy Lab (NREL) and, accordingly, integration scenarios are developed. A 63k-bus model of this system was constructed in the General Electric (GE) PSLF software package and is based on the previous work performed by the 2013 GE Energy Consulting and NREL for Eastern Frequency Response Study [4]. The previous databases are

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modified slightly from the Eastern Frequency Response Study [5] model here, however, to capture the effects of significant changes and the current online and available generation in the FirstEnergy system. The wind turbines are modeled as GE 3.6MW commercial wind machines [6].

This work is organized in two parts: Part 1 [7] addresses the short term faults' stability issues and the impacts of wind power. Part 2 discusses the long term faults and the associated stability issues. Long term faults refer to outage of generation unit(s) or a disconnection of lines by protective relays after a failure in clearing the fault or their immediate outage where the system's post-fault topology changes.

An extensive review of the current state of the art is provided in Part 1 of this work, the companion paper [7].

II. METHODOLOGY

The methodology discussed here, for transient stability analysis of power systems, focuses on methods and techniques that are for planning studies of offshore wind power plant integration projects. Here, the elements of this methodology that pertain to the analysis of long term faults are described. Those aspects of the methodology relevant to the analysis of short term faults are addressed in the companion paper [7].

The methodology studied in this paper consists of the following sequential steps:

1) In part I of this paper, it has been established that the first step for a reliable stability assessment of large-sale power systems is to identify the critical system' components whose consideration is crucial for a trustworthy transient stability analysis.

   In power systems, transient stability is a function of system's inertia, accelerating power of the fault, and rating capacity of the units [8]. Accordingly, in Part I of this paper, the critical system' components for the stability analysis following short term faults were selected on basis of two merits. The first merit was the significance of the amount of power that the components of interest generate or transmit to ensure that the accelerating power during the fault is maximal and allows capture of the relevant system dynamics. The second merit was their generation capacity which implicitly includes the generators' inertia and a significant portion of system's overall inertia. Then, the critical clearance time (CCT) metric, which refers to the longest clearing time that the system remains stable and none of the generators lose the synchronism, was used to identify the rotor angle stability margin of the system. The results from short-term faults revealed that there is a direct relationship between the capacity size of the faulted system' component and influence of integration offshore wind power plant on the CCT. Therefore, it is safe to rely on the results from analysis of short term fault for selecting the critical system' components for conducting transient stability analysis following long term faults. By considering the above-mentioned points, the key critical system' components for undertaking transient stability analysis following long term faults are chosen by:

   - **Generators**: The generator with the shortest CCT
   - **Transmission Lines**: The line with the shortest CCT

   This set of criteria implicitly includes the factors that influence the transient stability of power systems.

   In addition, to enhance the understanding of system's dynamics following integration of the offshore wind power plant, the offshore collector system must also be included.
2) The second step is to construct a base case by considering the power system without any offshore elements. This is accomplished by applying outages as sequentially events to each of the selected system' components (sans offshore components). The maximum rotor angle differences and deviations are an indication of whether or not the system is able to maintain its synchronism. In a stable power system, the maximum rotor angle difference deviation should settle close to zero within the first few seconds following a fault. Thus, for each of the faulted system' components considered, the maximum rotor angle difference deviation in the system should be computed to assess the rotor angle stability of the system.

   To assess the transient voltage stability, the Transient Over-voltage (TOV), Transient Low-voltage (TLV), Settling Voltage (SV) metrics are computed for each of the cases studied. These metrics are discussed in Part I of this paper [7]. Swing-Based Frequency Response (SBFR) index is a metric to evaluate the system's frequency response for all of the cases considered. The details for this metric are discussed in Part I of this paper [7].
3) The next step is to consider the entire system including the integrated offshore wind power plant. The analysis performed in the prior step is repeated within the context of the complete system. To examine the variability of the wind power plant, the system is examined at various levels of wind power plant power generation with suitable increments of generation selected over the wind power plant's operation range. The increments should be chosen based on the planner's experience and preference. For each of the cases studied, rotor angle difference and deviation must again be computed to assess the transient rotor angle stability performance, the TOV, TLV and SV to assess the transient voltage stability and the SBFR to assess system the frequency response.
4) Finally, the results from the base case are compared to those from the full system at different levels of wind power generation are compared. This comparison reveals how the type and size of the faulted system' components and the level of wind power generation influence transient stability of the power system following a long term fault.

III. CASE STUDY

This study considers integration of 1,000 MW of offshore wind power in Lake Erie into the FirstEnergy/PJM transmission system as a case study to verify the utility of the introduced methodology. This section describes the details of this case study and the computational implementation of this research.

A. FirstEnergy/PJM Power System

In this study, an accurate computer model of the PJM system is used. The PJM is a regional transmission operator in the Midwestern United States. It is part of the Eastern Interconnection and operates an electric transmission system. The FirstEnergy is a regional utility company, based in Akron, Ohio, within a geographical sub-region of the PJM and serves 6 million customers in Ohio, Pennsylvania, West Virginia, Virginia, Maryland, New Jersey, and New York.

The details of model development for this research is described in Part I [7] of this paper.

As a reminder, the main objective of this investigation is to study the impact of the integration of 1,000 MW of offshore wind power generation into the FirstEnergy/PJM transmission system. The second objective is to examine the impact of the retirement of the Perry Nuclear Power Plant, the largest single power plant in this area (1,280 MW and 625 MVar).

B. Computer Implementation

Computational implementation of large-signal stability analysis was carried out by a simulation. The reactive capability of the wind machines was assumed to have full capability (-43.0%/+57.8%MVar).

Accordingly, four cases were developed:

- **Case 1:** Perry online, SVC offline
- **Case 2:** Perry online, SVC online
- **Case 3:** Perry offline, SVC offline
- **Case 4:** Perry offline, SVC online

Detailed models of the FirstEnergy/PJM transmission system were used to analyze the aforementioned cases for each of the interconnection scenarios. After loading the steady-state models, generation dispatch, and load data, the wind models were initiated. Then the dynamic models of the system were loaded, including detailed representations of generators and their control systems, stabilizers, governors, dynamic loads, and other dynamic components of the grid. The GE's PSLF Version 18.1 01 80K, DYTOOLS simulation tool, was used to carry out this part of the study.

By relying on the proposed methodology in previous section, the following critical components were identified for the transient stability analysis in response to a long term fault:

1) Outage of the generator with the shortest CCT, Davis-Besse
2) Disconnection of the line with the shortest CCT, Davis-Besse to Lemoyne 345kV line
3) Outage of half of the offshore collector system (only in the cases considered with the offshore wind power plant present)

The offshore wind power plant was studied under multiple pre-disturbance operational points. The total duration of the simulation is 15 seconds, including 5 seconds pre-fault (to all startup transients to settle down) and 10 seconds post-fault to capture the transient dynamics resulting from the fault (occurred at t=5s). Following these faults, dynamic behavior of the generation units and transmission flows, including rotor angles, speeds, power generation and voltage profiles, in the FirstEnergy/PJM power area were recorded. During a 3-phase to ground short circuit, it is assumed that the system is symmetrical and the short circuit occurs simultaneously and identically on all three phases.

IV. RESULTS AND DISCUSSION

Following the loss of a major generation unit or transmission line, rotor speed of generators in the power area decrease due to an active power deficit. Subsequently, the difference synchronization between rotor angles begins to deviate. In a stable power system, the rotor speeds should regain their new operating point within few first seconds following an outage. It is normal that maximum rotor angle difference in a power area will experience an insignificant change, a few degrees. Otherwise, in case of an immense change and vast rotor angle difference, system may lose the synchronism which may lead to more serious consequences, including blackout. Figs. 1 through 3 show the maximum rotor speed and rotor angle deviations in this power area for different levels of wind power following the loss of the investigated system' components.

Fig. 1 shows that in the base case, following loss of Davis-Besse generator, maximum rotor speed deviation in this power area reaches almost zero within first 7 seconds and rotor angle difference in this power area changes within 0.2 degree. In all of the cases considered herein with offshore wind power plant, the maximum rotor speed deviation settles at 0.0007 p.u. The rotor angle difference in cases 1 and 2, in which Perry is online, settles at 0.8 degree deviation after a peak at 2.7 degrees, within first 10 seconds. The rotor angle difference in cases 3 and 4, in which Perry is offline, follow a trajectory similar to that of the base case and settles within 0.3 degree.

Fig. 2 shows that in the base case, following loss of Davis-Besse-Lemoyne line, the maximum rotor speed deviation in this power area reaches almost zero within first 8 seconds after some oscillations with the magnitude as high as 0.0045 p.u. The maximum rotor angle difference in this power area initially deviates up to approximately 2 degrees and then after the oscillations damped out, settles at zero within first 8 seconds. Upon integration of the offshore wind power plant, the maximum rotor speed deviation settles at almost zero within first 10 seconds, in all of the cases studied. In cases 1 and 2, in which Perry is online, the amplitude of maximum rotor speed deviation as high as 0.0023 p.u. This amplitude is approximately as immense as half of the greatest amplitude observed in the base case. In cases 3 and 4, in which Perry is offline, the amplitude of maximum rotor speed deviation is 0.0055 p.u. which is greater than the peak amplitude observed in the base case. The rotor angle difference in cases 1 and 2 settles at almost zero within first 10 seconds, after a few oscillations with similar damping ratio to the base case. The rotor angle difference in cases 3 and 4 settles at almost zero within first 10 seconds, after oscillations with a greater amplitude than observed in the base case, as high as 4.5 times.

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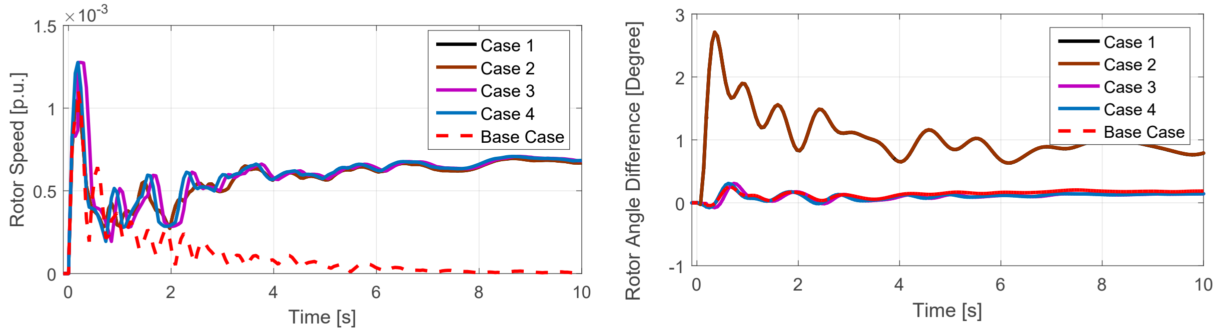
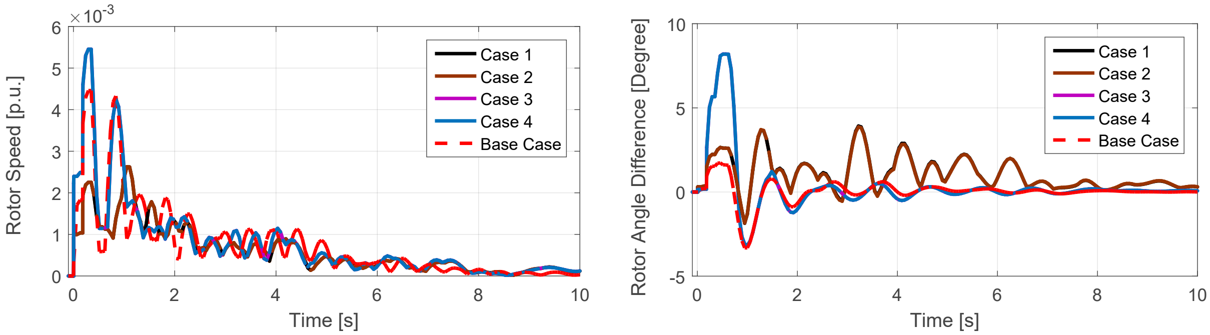


(a) Maximum Rotor Speed Deviation

(b) Rotor Angle Difference Deviation

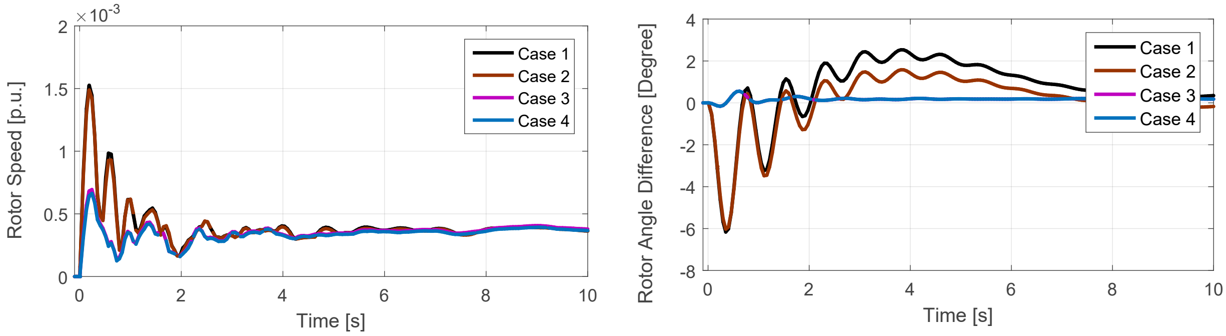
Fig. 1: Rotor angle and speed deviation in this power area following loss of Davis-Besse generator



(a) Maximum Rotor Speed Deviation

(b) Rotor Angle Difference Deviation

Fig. 2: Rotor angle and speed deviation in this power area following loss of Davis-Besse-Lemoyne line



(a) Maximum Rotor Speed Deviation

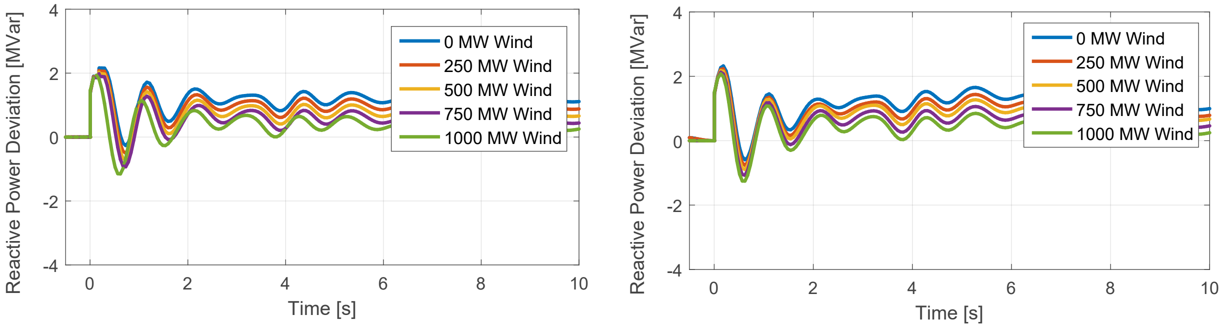
(b) Rotor Angle Difference Deviation

Fig. 3: Rotor angle and speed deviation in this power area following loss of half of offshore collector system

Fig. 3 shows that following loss of half of the offshore collector system, the maximum rotor speed deviation settles at 0.0003 p.u. within first 10 seconds. The maximum amplitude of rotor speed deviation is as high as 0.0015 p.u. in cases 1 and 2, in which Perry is online, and as high as is 0.0007 p.u. in cases 3 and 4, in which Perry is offline. The rotor angle difference in cases 1 and 2 settles at almost zero within first 10 seconds after a few oscillations with amplitude as high as 6 degrees. The rotor angle difference in cases 3 and 4 settles at almost zero within first 2 seconds with very modest oscillations.

By comparing the results from cases 1 and 2 with cases 3 and 4, for all of the cases presented in Figs. 1 and 2, it can be seen that, for a given level of wind power generation, the operation of Perry affects the amplitude of oscillations associated with rotor angle difference and the rotor speed deviation in this power area. The operation of Perry results in rotor speed deviations of a lower magnitude. However, for a given level of wind power generation, the operation of Perry did not affect the settling maximum rotor speed. These results also show that the operation of the SVC at the POI does not noticeably influence the rotor angle stability of the system following an outage.

Typically, the enhanced reactive power support by using the SVC or the wind machines with higher capability, allows the synchronous generators in the area to damp the rotor angle



(a) Without SVC

(b) With SVC

Fig. 4: Reactive power output of the generator 239085 for all of the cases considered, long term fault – For operation scenarios of with and without the SVC at the POI, for a given level of wind power, the reactive power output of the generators are approximately identical

TABLE I: Oscillatory modes appeared in the system following loss of Davis-Besse generator

	Base Case		**Case 1**		**Case 3**	
Mode No.	Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude
1	0.9 Hz	16.37	0.9 Hz	20.09	—	—
2	1.0 Hz	28.12	—	—	—	—
3	1.3 Hz	24.75	1.3 Hz	19.02	—	—
4	1.5 Hz	20.35	1.5 Hz	25.40	1.4 Hz	36.99

TABLE II: Oscillatory modes appeared in the system following loss of Davis-Besse to Lemoyne line

	Base Case		**Case 1**		**Case 3**	
Mode No.	Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude
1	0.9 Hz	116.66	0.8 Hz	18.12	—	—
2	1.0 Hz	179.76	1.0 Hz	123.62	1.0 Hz	129.82
3	1.3 Hz	405.45	1.3 Hz	377.13	1.3 Hz	292.72
4	1.4 Hz	110.37	1.4 Hz	298.61	1.4 Hz	102.92
5	1.5 Hz	121.27	1.9 Hz	170.23	1.5 Hz	119.36

TABLE III: Oscillatory modes appeared in the system following loss of half of the offshore collector system

	Case 1		**Case 3**	
Mode No.	Frequency	Amplitude	Frequency	Amplitude
1	0.2 Hz	10.33	—	—
2	0.5 Hz	27.93	0.7 Hz	17.48
3	0.9 Hz	31.94	0.9 Hz	20.62
4	1.0 Hz	17.42	1.0 Hz	14.87
5	1.3 Hz	59.22	1.2 Hz	27.57
6	1.4 Hz	85.52	1.5 Hz	19.89

swings following a fault and, effectively, improve the rotor angle stability [9], [10]. Nevertheless, the FirstEnergy/PJM system is tremendously rich in terms of available reactive power support, by having a great number of large synchronous condensers and the SVCs that are installed and operating all across the system. Hence, the operation of the SVC does not really aid the reactive output of synchronous generators in the area and, as a result, does not have a substantial impact on the transient rotor angle stability. This agrees with the findings from the Part I of this paper, the analysis of transient stability following short faults [7]. Fig. 4 shows the reactive power output of the generator 239085 in the area following the loss of Davis-Besse for all levels of wind power examined here. It can be seen that the results for cases without and with the SVC are fairly identical and, hence, it is safe to say that the enhance reactive support provided by the SVC at the POI does not aid the reactive power output of this machine. This generator is an arbitrary choice and the reactive power output of all of the other generators in the area for operation with and with the SVC at the POI is similarly identical and, therefore, not shown.

To provide a more comprehensive exhibition of the dynamic performance of this system, cases 1 and 3 are down-selected as basis for Prony analysis [11] on the active power generation signals from all of the generators in this power area to identify the dominant oscillatory modes that appear. The results of the Prony analysis are presented in Tables I through III.

The results presented in Table I show that three of the dominant modes which appear in the base case are eliminated in case 3. Comparatively, only one of the modes is eliminated in case 1. Nonetheless, those modes that remain, their amplitude considerably increases. In case 1 with Perry online,

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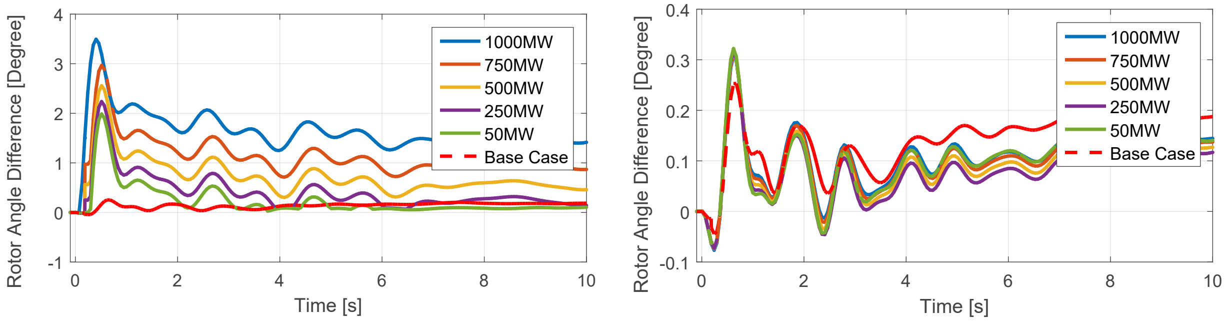
the amplitudes of oscillatory modes are intensified as high as %25. Whereas the case 3 with Perry offline shows as high as %81 increase in the amplitude of the modes.

The results shown in Table II reveal that the amplitude of all of the modes are reduced and the mode at 0.9 Hz is eliminated in case 3, comparing with the base case. In case 1, amplitude of the mode at 0.9 Hz is reduced by 90% from 116.66 to 18.12. The amplitude of the modes at 1.0 Hz and 1.3 Hz are also reduced while the amplitude of the modes at 1.4 Hz and 1.5 Hz are increased.

The results shown in Table III outline that the amplitude of all of the modes that appeared in case 1 are reduced in case 3 and the mode at 0.2 Hz is completely eliminated.

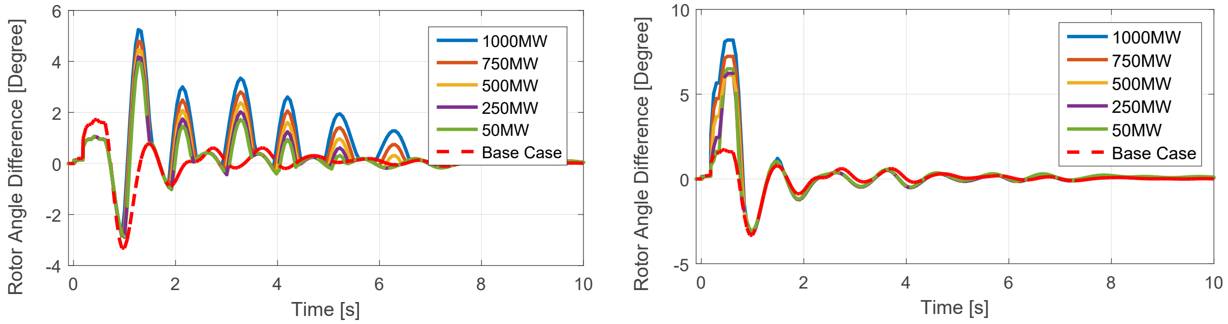
Figs. 5 through 7 contrast the impacts of variability of the offshore wind power plant on transient rotor stability of the system. These results show that the higher levels of offshore wind power can cause rotor angle oscillations with higher magnitude and higher settling rotor angle difference in the power area. Additionally, the operation of Perry here pronounces the effects of wind power plant variability. It also



(a) Case 1

(b) Case 3

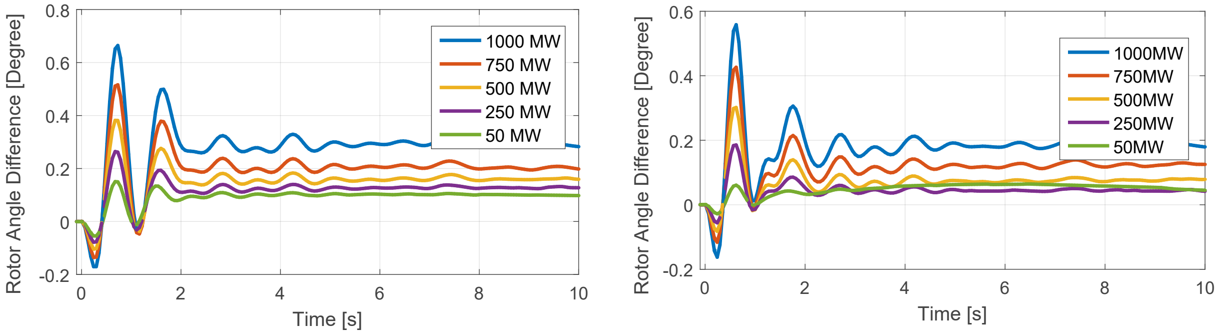
Fig. 5: Maximum rotor angle difference for different levels of wind power following loss of Davis-Besse generator in the cases studied



(a) Case 1

(b) Case 3

Fig. 6: Maximum rotor angle difference for different levels of wind power following loss of Davis-Besse to Lemoyne line in the cases studied



(a) Case 1

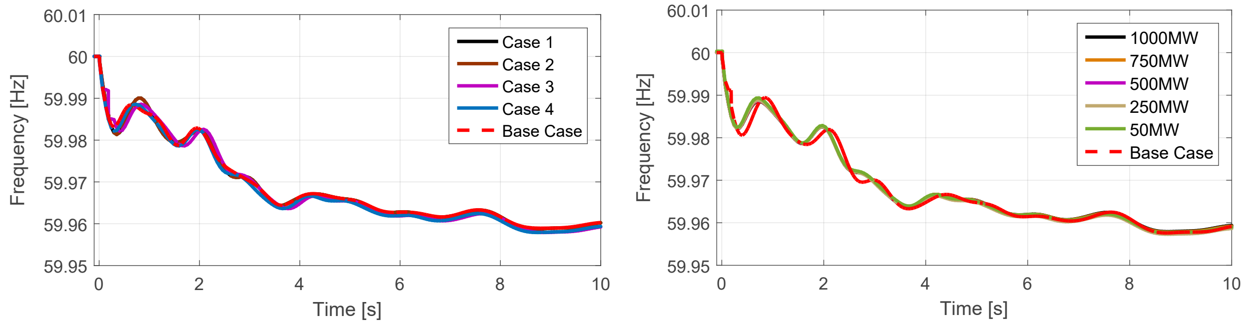
(b) Case 3

Fig. 7: Maximum rotor angle difference for different levels of wind power following loss of half of the offshore collector system in the cases studied

can be observed that maximum level of wind power generation provides the worst case scenario.

Heretofore, the results have established that the integration of the offshore wind power plant can overall improve the oscillations that appear in the FirstEnergy/PJM system following an outage by decreasing the number of modes that may appear. Nonetheless, their magnitudes may increase. In this case study, the changes in values of rotor angle differences and rotor speed deviations, in time-domain, after the integration of offshore wind power plant are very small and not an operational concern, less than 0.003 p.u. and 0.0007 p.u. for oscillation peak and settling values of the rotor speed deviation and 8 degree and 0.8 degree for oscillation peak and settling values of rotor angle difference in the area. Indeed, it can be concluded that the integration of offshore wind power plant does not attenuate the transient stability of the system examined here. Moreover, the higher the level of power generation by the offshore wind power plant, the higher the magnitude of the oscillations following long term faults. Hence, the maximum wind power can be classified as the worst case scenario.

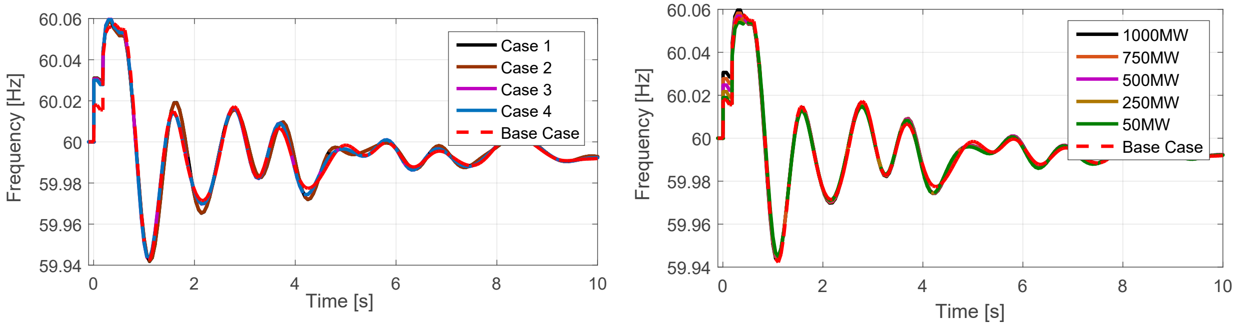
Figs. 8 through 10 show the transient frequency dynamics following the considered events. From these results, it can be seen that the frequency trajectory following faults on the onshore assets considered here, including those as the generators and the transmission lines, are identical in all of



(a) Comparison of the cases studied

(b) Comparison of level of wind power

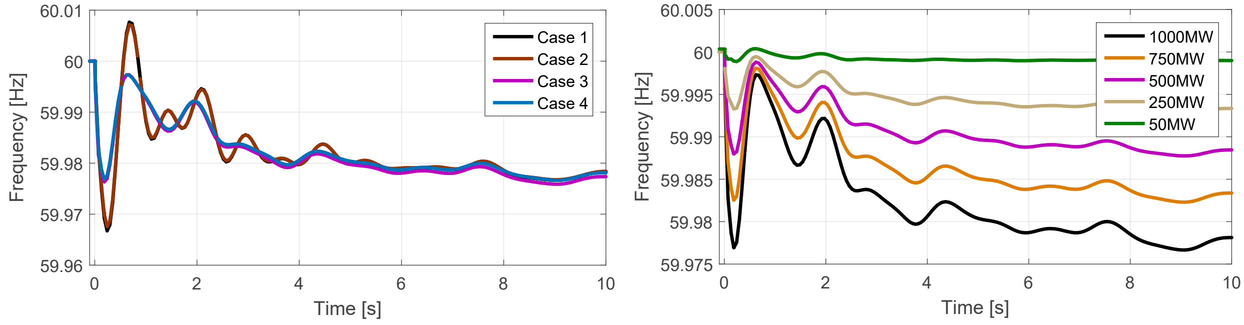
Fig. 8: Area frequency following loss of Davis-Besse generator in the cases studied



(a) Comparison of the cases studied

(b) Comparison of level of wind power

Fig. 9: Area frequency following loss of Davis-Besse to Lemoyne line in the cases studied



(a) Comparison of the cases studied

(b) Comparison of level of wind power

Fig. 10: Area frequency following loss of half of the offshore collector system in the cases studied

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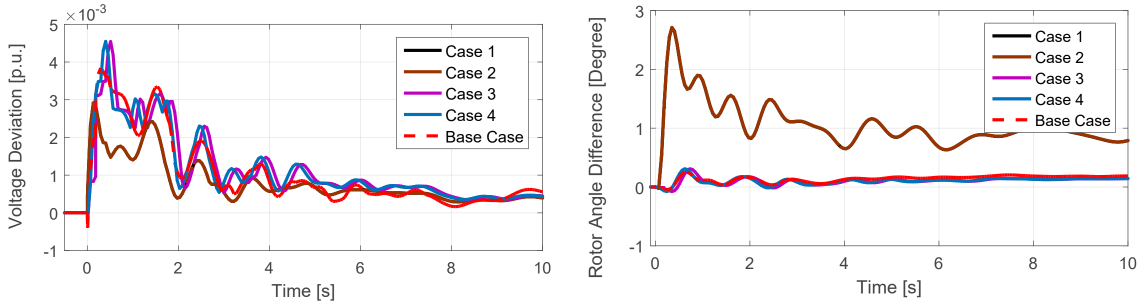
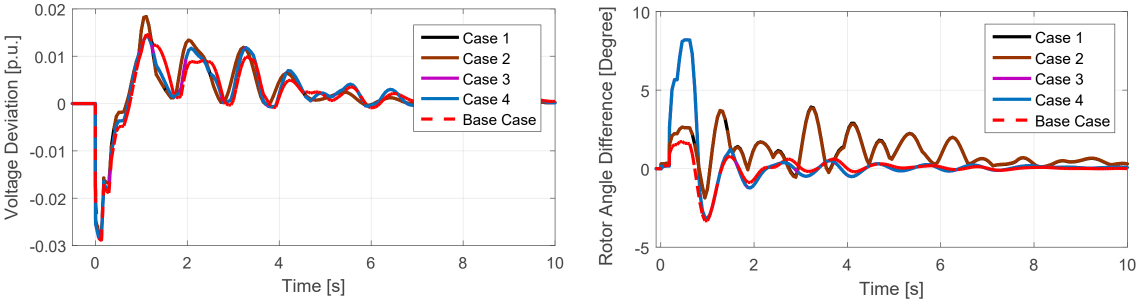


(a) Maximum voltage deviation

(b) Rotor angle difference

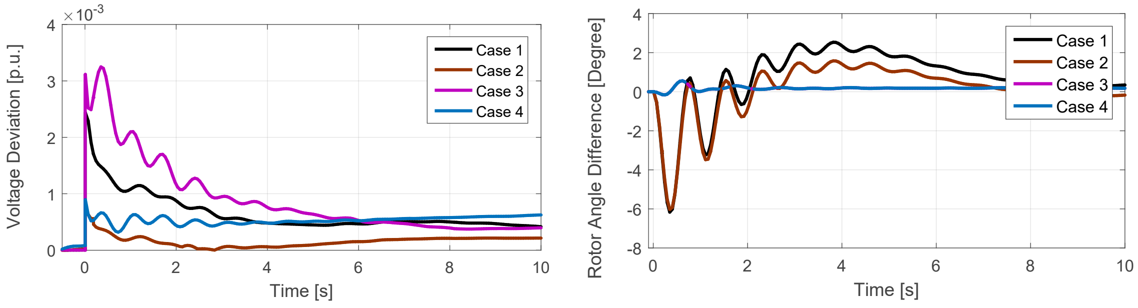
Fig. 11: Maximum voltage deviation and rotor angle difference deviation in this power area following the loss of Davis-Besse generator in the cases studied



(a) Maximum voltage deviation

(b) Rotor angle difference

Fig. 12: Maximum voltage deviation and rotor angle difference deviation in this power area following the loss of Davis-Besse to Lemoyne line in the cases studied



(a) Maximum voltage deviation

(b) Rotor angle difference

Fig. 13: Maximum voltage deviation and rotor angle difference deviation in this power area following the loss of half of the offshore collector system in the cases studied

the cases examined and for all levels of offshore wind power, including the base case. However, the area frequency following faults on the offshore system, as shown in Fig. 10, is a function of the operation of Perry and independent from the operation of the SVC at the POI. Moreover, following the considered faults on the collector system, it can be observed that the greater levels of power generation by the offshore wind power plant results in higher frequency drops and, subsequently, lower nadir and settling frequencies. In all of the cases considered here, the nadir frequency remained above the under frequency load shedding (UFLS) threshold, 59.5 Hz in Eastern Interconnection [12]. The lowest nadir frequency observed here is 59.94 Hz, following loss of the David-Besse to Lemoyne line. Additionally, the lowest settling frequency observed, similarly, is 59.96 Hz, following loss of Davis-Besse generator. In all of the cases studied herein, the results from cases 1 and 2 are identical. So are the results from cases 3 and 4.

The frequency response of a power system is defined by the area frequency behavior with respect to the level of blocked power. Table IV presents the results from the frequency response metric, SBFR, for the cases considered. This metric is a function of blocked active electrical power and area frequency swing during and following a fault.

TABLE IV: *SBFR* index for the cases studied to assess frequency stability of the system – 1000 MW wind generation

Fault	**Base Case**	**Case 1**	**Case 3**
Davis-Besse Generator	1,704	1,848	1,710
Davis-Besse to Lemoyne Line	808	815	815
Offshore Collector System	—	1,033	1,838

The results shown in Table IV indicate that the frequency response of the system following a long term fault is slightly improved by the integration of 1,000 MW offshore wind power plant. The SBFR metric for all of the cases studied here with offshore wind power plant is greater than the similar cases without the wind power plant. The SBFR for cases 1 and 2 are identical, as the system frequency results in time-domain are, and, therefore, the results from case 2 are not shown. So are for cases 3 and 4. The SBFR values that are shown in this table are computed for 1,000 MW power generation offshore wind power plant as, earlier in this paper, the operational condition of the maximum wind power has been established for the worst case scenario.

Figs. 11 through 13 illustrate the relationship between the deviation in rotor angle difference and the maximum voltage deviation in this power area for the cases studied here.

From the results shown in figure 11, it can be seen that, after the integration of the offshore wind power plant, following the loss of Davis-Besse generator, the damping ratio for the maximum voltage deviation remains similar as they are in the base case while their amplitude is subject to the operation of Perry, in all of the four cases considered here. The results from the loss of Davis-Besse to Lemoyne line, shown in Fig. 12, are also consistent with this observation. However, for both faults, the changes in the amplitude of voltage oscillations is very small and, therefore, negligible. Following the loss of the offshore collector system, as shown in Fig. 13, there is a direct relationship between the deviation of rotor angle difference in this power area and the operation of Perry. Whereas the maximum voltage deviation in this power area is dependent upon the operation of the SVC at the POI; it improves the transient voltage stability of the system. This agrees with the findings presented in [13].

From the current observation, it can be concluded that, following the integration of an offshore wind power plant, the transient voltage oscillations in the system are independent from the rotor angle oscillations in the area for all levels of wind power.

The settling voltage deviations observed at almost zero in all of the cases examined here and for all levels of wind power. This indicated that voltage at the faulted system' components recovers to its pre-fault value within first 10 seconds following the long term fault. Thus, measures of transient voltage stability in this system exist.

V. CONCLUSION

This paper develops a practical and scalable methodology for transient stability analysis of power system for planning studies of offshore wind power plant integration projects. This research investigates the specific case of integrating 1,000 MW of offshore wind power into the FirstEnergy/PJM service territory using a realistic model of 63k-bus test system that represents the U.S. Eastern Interconnection as a case study.

This study is organized in two parts: Part 1 addresses the short term faults' stability related issues. Part 2 discusses the long term faults and associated stability issues. Long term faults refer to outage of generation unit(s) or a disconnection of lines by protective relays after a failure in clearing the fault where the system's post-fault topology changes.

The results of this paper, Part 2 of this study, show that integration of an offshore wind power plant can improve the transient stability of the overall system by decreasing the number of the oscillation modes present following a fault. They also show that operation of the SVC at the POI does not influence the rotor angle stability of the system following an outage. The results all reveal that the maximum level of wind power generation provide the worst case scenario in terms of rotor angle oscillations.

The SBFR metric is used to assess the frequency stability. The results suggest that for system' frequency response studies, the worst case scenario is the maximum wind power generation.

The results from the voltage stability analysis demonstrate that, upon the outage of onshore system' components, the voltage oscillations are unaffected by the integration of offshore wind power plant for all cases considered. In addition, following the loss of offshore system's components, additional reactive power support at the POI improves the ability of the system to damp out the voltage oscillations.

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