



Transmission system protection screening for integration of offshore wind power plants



A. Sajadi ^{a,*}, L. Strezoski ^a, K. Clark ^b, M. Prica ^a, K.A. Loparo ^a

^a Department of Electrical Engineering and Computer Science, Case Western Reserve University, Cleveland, OH, USA

^b Power Systems Engineering Center of the National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA

ARTICLE INFO

Article history:

Received 20 July 2017

Received in revised form

28 January 2018

Accepted 15 February 2018

Available online 21 February 2018

Keywords:

Offshore wind integration

Protection screening

Transmission system

ABSTRACT

This paper develops an efficient methodology for protection screening of large-scale transmission systems as part of the planning studies for the integration of offshore wind power plants into the power grid. This methodology avails to determine whether any upgrades are required to the protection system. The uncertainty is considered in form of variability of the power generation by offshore wind power plant. This paper uses the integration of a 1000 MW offshore wind power plant operating in Lake Erie into the FirstEnergy/PJM service territory as a case study. This study uses a realistic model of a 63,000-bus test system that represents the U.S. Eastern Interconnection.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Electrical short-circuits are the most common faults in power systems. Therefore, protective devices are meant to prevent any damage to the assets or long-term power delivery disruption as a result of electrical short-circuits. During the system planning studies, the specifics and requirements of these devices are determined through short-circuit screening analysis.

Wind integration projects typically involve adding new wind generation units to an existing power system. After an offshore wind power plant is integrated into a power system, the topology and dynamics of the system changes. Therefore, it is essential to re-assess a variety of facets of the system's operation, including its protection, considering the volatility of wind power plants [1]. In terms of protection system, it is required to assess whether the protection equipment remain capable of interrupting the faults and short-circuit current as they are meant to do. In case of incapability, they need to be replaced or upgraded to meet the grid's requirements.

Wind power plants can be integrated into a power system through transmission and distribution systems, depending on their

generation capacity. The power plants that are integrated through the high voltage transmission systems are large-scale wind power plants in scales of 100s–1000s of MW including offshore wind power plants. The smaller scale wind power plants are typically connected to the medium voltage or low voltage networks.

Considering the above-mentioned concerns, the main objective of this research is to tackle the effects of integration of offshore wind power plants on protection system of large-scale transmission systems at the system level and screening whether any upgrade for the protection system is needed.

During the past three decades, the protection and relaying problems and short-circuits in classical power systems that operate in the conventional vertical structure including bulk generation and passive loads, have been extensively studied and well-documented [2–6]. The current state of the art regarding the challenges related to protection and relay schemes at the system level in the presence of renewable energy focuses on distribution networks and micro-grids, with a dominant focus on land-based wind power plants [7–14]. The literature that addresses issues related to protection and relays for offshore wind power plants mainly centered on two domains: (1) protection of the offshore wind power plants [15,16], [17,18], and (2) small-scale electric power systems [19–21]. The authors of [15] investigated the fault response and protection on the offshore equipment, including collector and export cables of an offshore wind power plant without detail investigation of the onshore transmission system. The design of protection relays for wind power plants is elaborated in Ref. [16]. The author of [17]

* Corresponding author.

E-mail addresses: axs1026@case.edu (A. Sajadi), lsx533@case.edu (L. Strezoski), Kara.Clark@nrel.gov (K. Clark), mvp438@case.edu (M. Prica), kal4@case.edu (K.A. Loparo).

analyzed fault conditions and effective fault ride-through and protection schemes in the electrical systems of offshore wind power plants. Protection coordination of the electrical apparatus within a wind power plants is discussed in Ref. [18]. The research presented in Ref. [19] exhibits an apparent impedance calculation method that utilizes the bus impedance matrix to calculate the impedances viewed by distance relays during a fault close to the point of interconnection (POI) for a grid with an HVDC-connected offshore wind power plant and uses the IEEE 39-bus test system for verification.

Accordingly, the main contribution of this paper is the development of an efficient methodology for protection screening step of transmission system planning studies that includes integration of offshore wind power plants into the power grid. This methodology relies on understanding of dynamics of the system and is scalable, practical, and easy to implement for large-scale power systems. This study considers the uncertainty in form of variability of the power generation by offshore wind power plant.

This paper considers integration of a 1000 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 the offshore plant and the POI 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 has been constructed in 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 [22]. The previous databases are modified slightly from the Eastern Frequency Response Study [23] 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 3.6 MW commercial wind machines [24].

2. Short-circuits in power systems

As previously stated, electrical short-circuits are the most common faults in power systems. It is very important to identify and understand the behavior of a system during a fault and after its clearance because if the system's variables exceed the thresholds of the protective relays, then the protective devices will operate to protect the system. Their malfunction or failure to operate properly can cause a severe damage to network assets or cause an unexpected restriction of power delivery.

The short-circuit and protection analysis is associated with three stages: (1) pre-fault, (2) fault and (3) post-fault.

During the pre-fault period, the system is stable and operating at its equilibrium.

As the fault occurs, a short-circuit current (SCC) begins to flow through the faulted components. During the fault, the system manifests a transient behavior that could potentially lead to instability or severe damage to equipment or personnel. The reason for this behavior of the components during faults is the change in parameters or structure of the system. For instance, in a synchronous generator the sub-transient reactance could be 10 times smaller than that of the steady-state reactance [2]. In case of a ground fault on transmission lines, the impedance between the generator and the ground drops significantly; subsequently, the fault circuit current could be up to 25 times greater than the nominal current [14] and the voltage drops to nearly zero.

The post-fault period refers to post-clearance time frame of the fault during which the system attempts to restore its stable operation. This can cause transient overvoltage (TOV) at the faulted components.

The North American Electric Reliability Corporation (NERC) Standard TPL-001-2 [25] addresses transmission system planning performance requirements and requires that a system's short-circuit model and analysis include any planned generation and transmission facilities in service that could impact the study area. The majority of transmission lines are protected by circuit breakers; therefore, in transmission system planning and expansion studies it is necessary to investigate the SCC and TOV of the system and how they may change upon an elements replacement and system reconfiguration to identify the upgrades needed. The SCC refers to the current that flows through the faulted line during the fault period. Whereas the TOV defines the highest recovery voltage that occurs during the post-fault period at the faulted line. These two metrics are the most important factors to assess the capability of lines' circuit breakers.

The IEEE Standard C37.011 [26] defines that for a proper application, the TOV capability of the breaker must be greater than the transient overvoltage of the system during the post-fault period. Additionally, its SCC interrupting level should be greater than the short-circuit current that it is intended to arrest during a fault. The transient overvoltage capability of a breaker is a function of the breaker's voltage rating and its SCC interrupting level [26]. These are to ensure that the circuit breaker is capable of interrupting the fault.

3. Methodology

The objective of this study is to assess the impacts and contribution of offshore wind power plants on short-circuits to identify whether transmission system protection upgrades may be required.

Traditional methods to calculate short-circuits models in power systems with bulk synchronous generators have been well established in the literature [2–6]. As the power systems are becoming larger, more uncertain, nonlinear, and complex, consequently, the calculation of its short-circuit models are becoming more sophisticated, computationally burdening, and problematic as well. In large-scale power systems, real-time simulations could be carried out for short-circuit analysis. In these types of studies, usually the effect of load fluctuation could be neglected [27].

Having the above-mentioned issues in mind, the following section describes the methodology of this study.

In large-scale systems with 1,000s to 100,000s of lines, it can be computationally burdening and inefficient and overly time consuming, nearly impossible, to screen every single line. Therefore, the first step is to identify the correct critical lines to undertake the short-circuit analysis. The criteria to identify the critical lines to screen can be described by:

1. In the literature [2,28], it has been established that the severity of a fault is a function of the distance between the fault location and the source of power generation. The intention of this study is to identify the effects of the integration of offshore wind power generation on an existing transmission system's fault response. Therefore, fault locations relative to their distance from the POI are within the interest. As a result, the first criterion for identifying the critical transmission lines to conduct short-circuit analysis and protection system screening should be on basis of their electrical distance from the POI.
2. During a fault, the dynamics of a power system could be approximated by [1]:

$$\frac{d^2 \delta_e}{dt^2} \approx \frac{P_{fault}}{H} \quad (1)$$

where δ_e refers to the electrical rotor angle, P_{fault} is the blocked electrical power during the fault, and H is the inertia of the system.

From (1), it can be seen that the severity of a fault is proportional to the blocked power during the fault. Therefore, the second criterion to identify the critical transmission line for the short-circuit analysis should be on basis of the distinction of the active power that lines transmit.

3. Dynamic of rotor angles (stability) in power systems is directly related to the inertia of the system [2], as shown in (1). In particular, it has been shown that the dynamics of rotor angle is a function of the electrical distance between the faulted components and an inertia-contributing unit and the level of inertia provided [1]. Additionally, there is a direct relationship between voltage and rotor angle behaviors following a fault in power systems [29]. Therefore, there is a relationship between voltage recovery at a faulted component following a fault clearance and its electrical distance from an inertia-contributing unit. As a result, the electrical distance of the lines from inertia-contributing units and the level of inertia provided should be also the criteria for identifying the critical transmission lines to screen.

To this end, three main criteria have been highlighted for identifying critical transmission lines for screening process: (1) the electrical distance from the POI, (2) the level of active power transfer, and (3) the electrical distance from the inertia-contributing units.

It should be noted that the electrical distance is relative to the size of the system and is associated with the length of the transmission lines. Additionally, the number of lines to undertake the screening study depends on the level of reliability that the system requires to reach. Therefore, assessing the electrical distance in identifying critical lines to screen as well as the number of lines to screen rely on the planner's experience and preference, size of the system, available computational resources, and the project's requirements.

Once the lines are identified, following procedure should be conducted:

1. After identifying the critical transmission lines, the subsequent step is to apply credible short-circuit faults to each of the components as individual events in the system without a wind power plant (i.e., the base case). For each event, the SCC and TOV metrics should be computed. The SCC and TOV are the current that flows through the faulted line during the fault period and the highest recovery voltage that occurs during the post-fault period at the faulted line, respectively. The faults should be chosen based on the system's historical data and its credible contingencies.
2. To evaluate the impacts and contribution of the offshore wind power plant on the SCC and TOV, the next step is to repeat the same procedure and apply the same faults to the considered lines in the power grid with the integrated wind power plant.
3. To quantify the variability of the wind power plant, the level of power generation of the wind power plant should be incremented with credible steps throughout its full operational range. The step sizes should be chosen based on the planner's experience and preference based on the available computational resources and size of the system. For each step, the SCC and TOV for the fault on each of the lines should be computed.
4. Finally, by comparing the results, the impacts of the wind power plant and its operation's contribution to the SCC and TOV could be identified. The results provide a good approximation of whether any upgrade to protection system is required to maintain reliability with the integration of the wind power plant.

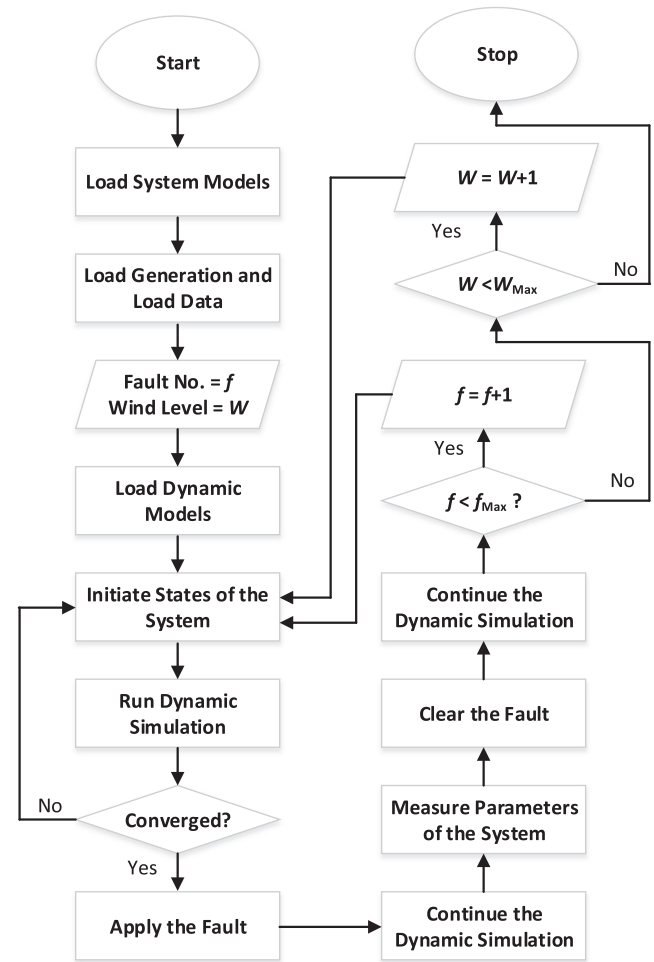


Fig. 1. Flowchart describing the methodology proposed in this research — f refers to a fault on a line within the list of identified critical lines, f_{max} refers to the fault on the last line in the list of considered credible line faults, W refers to the level of power generation by the wind power plant, W_{max} refers to the maximum level of power generation by the wind power plant.

The block diagram of the described procedure is presented in Fig. 1.

It should be noted that this methodology is a screening process and scrutinize the SCC and TOV of the critical transmission lines during fault and post fault clearance. Therefore, detailed information on operating protection scheme such as relays used in the protection scheme and their characterization is not required. However, upon identification of a major change in these measures, further action and detailed studies on implemented protection schemes are required which are beyond the scope of this research.

4. Case study

This study considers integration of 1000 MW of offshore wind power in Lake Erie into the FirstEnergy/PJM transmission system as a case study. This section describes the details of this case study and the computational implementation of this research.

4.1. FirstEnergy/PJM power system

In this study, a realistic 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 subregion of the PJM and serves 6 million customers in Ohio, Pennsylvania, West Virginia, Virginia, Maryland, New Jersey, and New York.

4.2. Wind power integration scenario development

The estimated geographic distribution of available wind power over the surface of Lake Erie was provided by the NREL, and, based on these estimates, the candidate POI was identified in the FirstEnergy transmission system. Accordingly, a scenario for the integration of a total of 1000 MW of offshore wind generation at a single POI located in North Perry, Ohio (situated within the FirstEnergy/PJM system on a site on Lake Erie, 40 miles (65 km) Northeast of Cleveland, Ohio), subject to compatibility with the extant grid infrastructure, was developed. Fig. 2 shows the geographical location of the offshore wind power plant and this POI.

4.3. Offshore wind power plant model development and computer modeling

For computational purposes, the 1000 MW offshore wind power plant is treated as two groups of generators, each of 500 MW, that are aggregated through a 34.5 kV collector system. Consequently, each of these groups is modeled as a single 500 MW generator and the outputs of the generator pair are aggregated in an offshore collector system connected to the POI bus through six export cables.

The authors of [13] and [14] suggest that the type 3 wind generators, doubly-fed induction generator (DFIG), produce the highest short-circuit currents. Therefore, this class of machine was considered in this research. The wind turbine model parameters

used in this study are based on a Type 3 GE 3.6 MW offshore wind turbine [24].

The specific dynamic models of the offshore wind generation system used to construct the simulation discussed here are those defined in GE's PSLF model library [30]. The principal model elements used are:

- *wndtge*: the wind turbine and turbine control model for GE's DFIG wind turbines
- *gewtg*: the generator/converter model for GE's DFIG wind turbines
- *exwtge*: the excitation (converter) control model for GE's DFIG wind turbine generators.

The substation transformer is rated on the basis of the wind turbine generators and has a typical impedance of approximately 8% [31].

Static VAR compensator (SVC) with significant compensation capacity was inserted at the POI in the computational model. The level of reactive power generated/consumed by the SVC was monitored during simulation to determine the capacity of the compensation device required for providing ancillary services to the grid. The dynamic model used to represent this device is a simple Static VAR device, VWSVC in GE's PSLF model library [30]. The analysis considered a maximum/minimum SVC rating of ± 500 MVar.

More information about these models is available in GE's PSLF documentation [30].

4.4. Generation dispatch scenarios and load assumptions

The main objective of this investigation is to study the impact of the integration of 1000 MW of offshore wind power generation into the FirstEnergy/PJM transmission system. To this end, the winter



Fig. 2. Map of location of the considered 1000 MW offshore wind power plant, 17.4 miles off the shore of Lake Erie in Perry, Ohio.

2013 load data from the Eastern Interconnection were modeled in PSLF. This model contains 63,608 system buses and 8356 generators, with a total of 894,772 MW and 411,288 MVar of installed generation capacity to serve a load of 302,086 MW and 75,596 MVar.

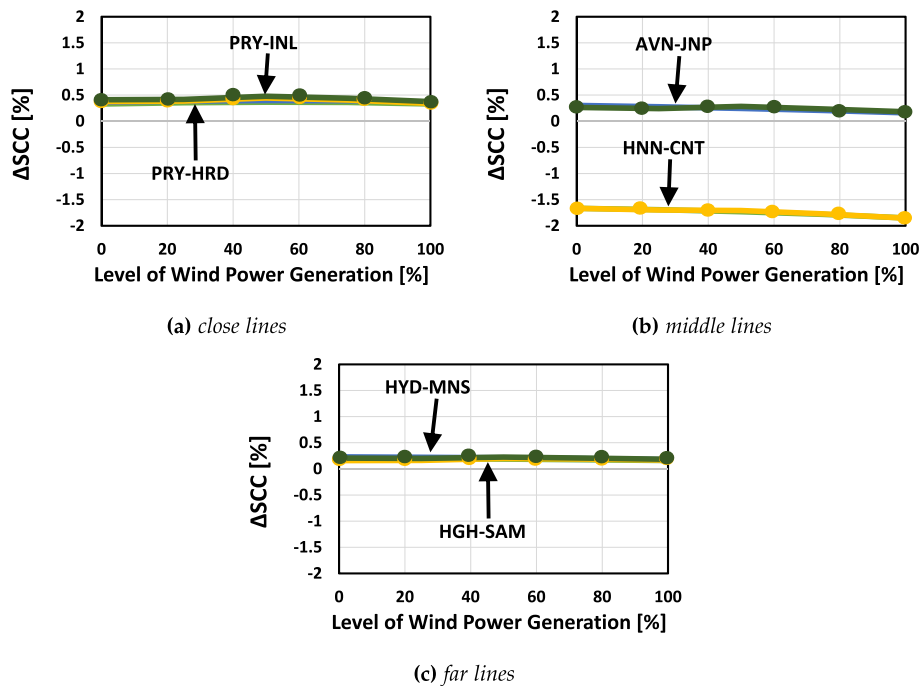
5. Computational implementation

The computer simulation was carried out using GE's PSLF Version 18.1 01 80K, DYTOOLS simulation tool. Accordingly, two cases were developed: (1) SVC offline and (2) SVC online. This research uses an integration scenario with a single POI. When there are multiple POIs, the same procedure could be carried out.

Detailed models of the FirstEnergy/PJM transmission system were used to analyze the aforementioned cases. 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.

Six lines were identified for this study subject to their electrical distance from the POI, their highest active power transfer rate, and their distance from inertia contributing units and the level of inertia provided:

1. Close lines: Most heavily loaded lines close to the POI:
 - (a) Perry to Inland (PRY-INL)
 - (b) Perry to Hardin (PRY-HRD)
2. Middle lines: Most heavily loaded lines neither near to nor far from the POI:
 - (a) Avon to Juniper (AVN-JNP)
 - (b) Hanna to Canton (HNN-CNT)
3. Far Lines: Most heavily loaded lines far from the POI:
 - (a) Hoytdale to Bruce Mansfield (HYD-MNS)
 - (b) Highland to W.H. Sammis (HGH-SAM)



The lines with * represent the cases with operating SVC at the POI

Fig. 3. Impact of offshore wind power plant on SCC in the lines studied.

It should be noted that the defined distance here is relative to the size of the FirstEnergy/PJM system and length of lines in this power area.

In terms of inertia criterion; five of these lines, except Hanna to Canton line, are directly interconnected to power plants with a variety of inertia contribution, including Perry (1200 MW), Bruce Mansfield (2497 MW), W.H. Sammis (2156 MW), and Avon (758 MW). This combination allows to demonstrate different scenarios of direct and indirect connection to an inertia-contributing units with a variety of inertia contribution.

The faults considered in this study are symmetrical three-phase-to-ground short-circuits. The fault clearance time is 4.5 cycles and the location of the faults are assumed to be exactly in the middle of the line.

The offshore wind power plant was studied under multiple pre-fault operational levels. The total duration of the simulation is 15s, including 5s pre-fault (to all startup transients to settle down) and 10s for fault and 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 in the FirstEnergy/PJM power area were recorded.

6. Results and discussion

This section exhibits the results from the cases studied. First, the results from the SCC analysis are provided and, then, the results from the TOV are presented.

6.1. Short circuit-current

The results of the SCC which flows through the studied lines during a fault are presented in Fig. 3 using ΔSCC measure. This measure represents the percentage of change in the SCC as a result of integration of the offshore wind power plant into the FirstEnergy/PJM power grid.

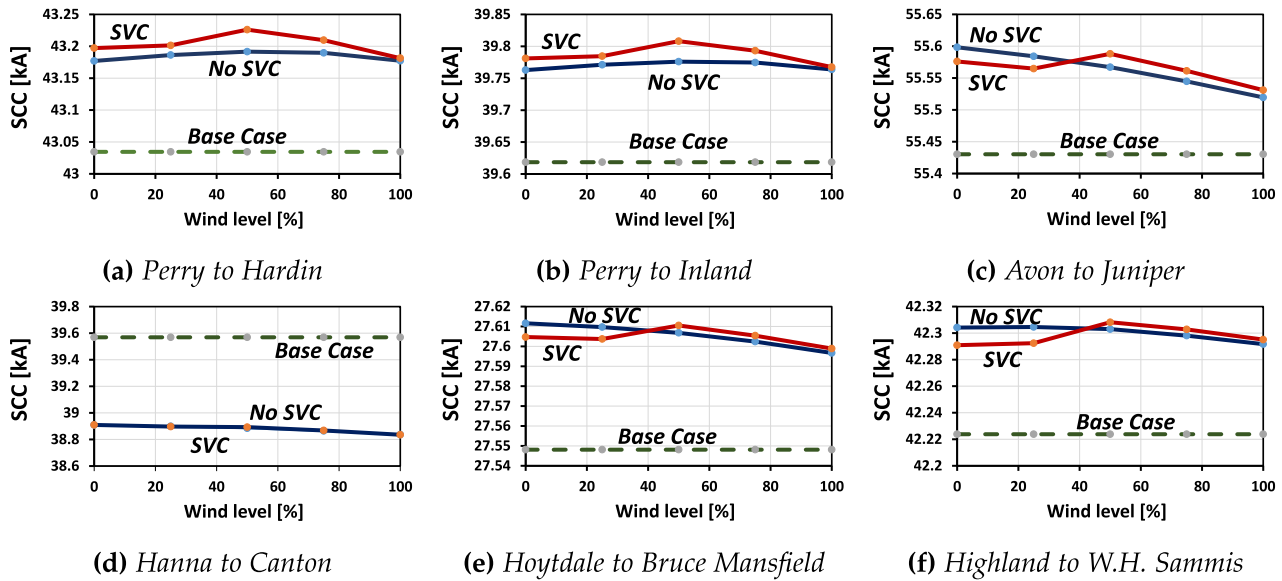


Fig. 4. The actual value of SCC in the lines studied.

Fig. 3a shows that the level of SCC for the faults on the close lines increases by up to 0.5%, consistently for all levels of wind generation and in both considered lines – Perry to Inland and Perry to Hardin lines. In addition, the results from the cases – with and without operating SVC at the POI – are identical. Thus, it can be seen that the operation of SVC does not improve or degrade the SCC in the close lines. It should be noted that the plots distinguishing the cases with and without SVC are identical for both lines and are overlapped in Fig. 3a.

The results shown in Fig. 3b outline that the level of SCC for the fault on Avon to Juniper increases for up to 0.3%. For fault on Hanna to Canton line, the SCC decreases by up to approximately 2%. In addition, the variations of Δ SCC throughout the increment of wind power for both lines are very small and negligible. Similar to the observation from the results for the close lines, the operation of SVC at the POI does not influence the SCC in the middle lines. The plots highlighting the cases with and without SVC are overlapping in Fig. 3b.

The results shown in Fig. 3c reveal that the level of SCC for the faults on the far lines, Highland to W. H. Sammis and Hoytdale to Bruce Mansfield lines, increases by less than 0.2% in both lines, consistently, for all levels of wind. Moreover, similar to the observation from the previous results, the results here indicate that the operation of SVC at the POI does not influence the SCC in the far lines. The plots characterizing the cases with and without SVC are identical for both lines and are overlapped in Fig. 3c.

The actual values of SCC for the cases studied are plotted in Fig. 4. In these plots, the dashed green line indicates the base cases (the system without a wind power plant), and solid red and blue lines indicate the cases that include offshore wind power plant with and without SVC operating at the POI, respectively.

From the presented SCC results in this section it can be seen that the greatest SCC increase, upon integration of the offshore wind power plant, occurs in the, electrically, closest lines to the POI. This agrees with previous suggestions by Refs. [7,2,27]. Hence, it can be said that the more distant the line is from the POI, the less influence the integration of offshore wind power plant has on the SCC. In this particular case study, the level of increase in the SCC remains less than 0.5%, 191.6 A.

The results for all cases studied reach a consensus that the contribution of SVC to the Δ SCC is very small and insignificant. In

this case study, the greatest difference that operation of SVC makes in SCC is 34.5 A.

The results here also suggest that the volatility of the offshore wind power plant is fairly inconsequential with respect to the SCC for its entire operational span. Therefore, two operational scenarios of 100% and 0% offshore wind power generations can be marked as critical scenarios that provide necessary information for the entire operational span of the wind power plant.

It should be noted that the DFIGs' fault response can vary significantly. For severe faults, the DFIGs will lose their control and their fault currents can be as high as 10 times their rated currents [32–34]. This paper considers this operational condition as it is the most critical scenario.

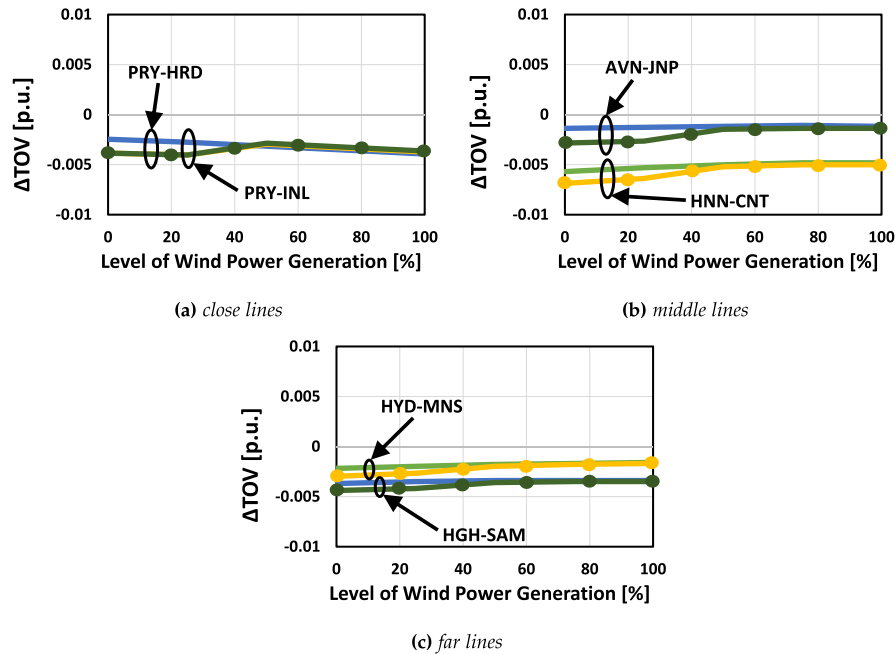
6.2. Transient overvoltage

The results from the TOV analysis during the post-fault recovery for the cases studied are presented in Fig. 3 using Δ TOV measure. This measure represents the per-unit change of the TOV as a result of integration of the offshore wind power plant into the FirstEnergy/PJM power grid.

Fig. 5a shows that the level of TOV for the faults on the close lines – Perry to Inland and Perry to Hardin lines – decreases in both lines within 0.002 p.u. at 0% wind power and 0.004 p.u. at 100% wind power, linearly and proportional to increment of power generation by the offshore wind power plant. Moreover, the operation of SVC at the POI slightly improves the TOV within a range of 0%–50% of wind generation. It should be noted that the plots for both lines, for the cases with and without SVC, are identical and overlapping in Fig. 5a.

The results illustrated in Fig. 5b show that the level of TOV for the faults on the middle lines decreases; by up to 0.003 p.u. in the Avon to Juniper line and by up to 0.007 p.u. in the Hanna to Canton. Similar to the observation from the results for the close lines, the results here show that the operation of SVC at the POI slightly improves the TOV in middle lines within range of 0%–50% of wind generation. In cases with no SVC operating at the POI, the results for all levels of wind power generation varies insignificantly, resulting in an approximately fixed Δ TOV value for all levels of wind power generation.

The results shown in Fig. 5c outline that the level of TOV for the



The lines with * represent the cases with operating SVC at the POI

Fig. 5. Impact of offshore wind power plant on TOV in the lines studied.

faults on the far lines decreases; by up to 0.005 p.u. in the Highland to W.H. Sammis line and by up to 0.003 p.u. in the Hoytdale to Bruce Mansfield line. Similar to the previous cases, the operation of SVC at the POI slightly improves the TOV in far lines within a range of 0%–50% of wind generation. The results from the case without a SVC operating at the POI exhibit a constant ΔTOV value for all levels of wind power generation.

The actual values of TOV for the cases studied are plotted in Fig. 6. In these plots, the dashed green line indicates the base cases (the system without a wind power plant), and solid red and blue lines indicate the cases that include offshore wind power plant with and without SVC operating at the POI, respectively.

The presented TOV results in this section highlight that the highest ΔTOV occurred in the middle lines. In fact, the ΔTOV manifests a noteworthy dependence on the electrical distance between the fault location and an inertia contributor and the level of inertia provided. In this case study, five of the identified lines, except Hanna to Canton line, are directly interconnected to inertia-contributing power plants including Perry, Bruce Mansfield, W.H. Sammis, and Avon. As a result, it can be seen that the effect of change in the TOV is more pronounced in case of the Hanna to Canton, the line without a direct interconnection to any inertia-contributing unit. Additionally, the level of inertia provided by the units also matters. To notice this, in far lines, there is

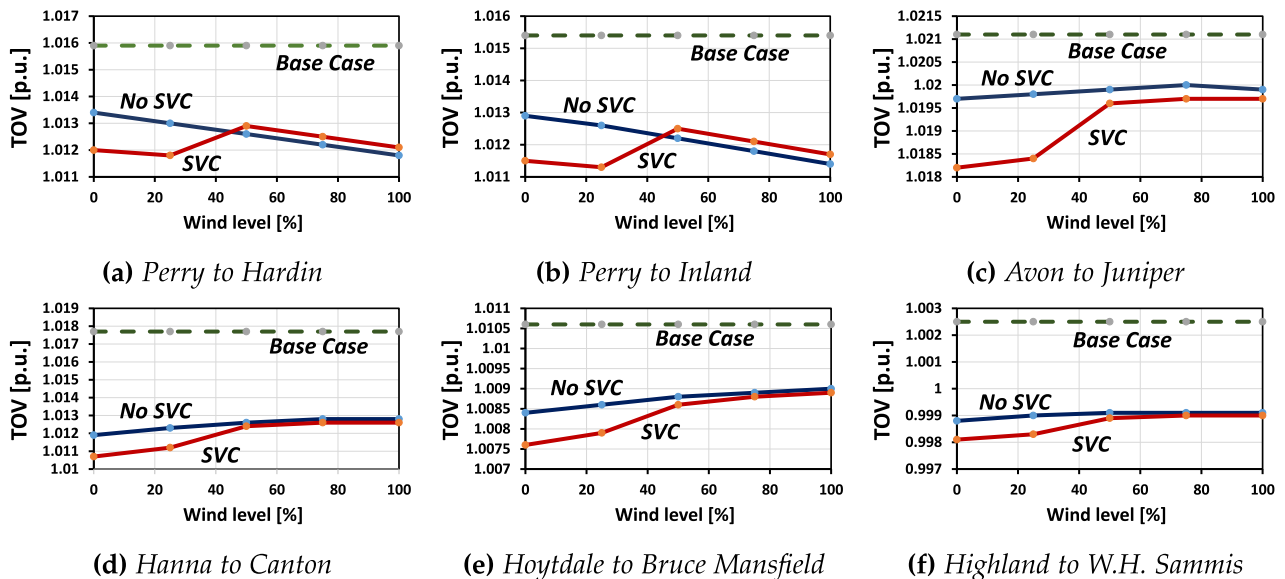


Fig. 6. The actual value of TOV in the lines studied.

a less TOV change in the Hoytdale to Bruce Mansfield line than in the Highland to W.H. Sammis line as the capacity and inertia provided by the Bruce Mansfield is greater than the W.H. Sammis. Hence, the TOV is less affected. In close lines, both lines – Perry to Inland and Perry to Hardin line – are interconnected to the Perry power plant and, thus, the level of change in TOV is identical for both lines.

The results also exhibited that the contribution of SVC to the Δ TOV is very insignificant; less than 0.001 p.u. in this case study. The authors of [35] discussed the SVC operation for the offshore wind power plants and its impact on the transient stability of a system including its voltage recovery for a variety of faults. They have demonstrated that the use of SVC is not effective for improvement of voltage recovery following short-term faults. Having this in mind, the results presented here agree with their suggestion.

The results from all the cases studied proved that the TOV remains approximately unchanged with respect to change of wind power. Thus, the information regarding Δ TOV from the operational scenarios of 100% and 0% offshore wind power generation sufficiently quantifies the volatility of wind over the entire operational span. In very large systems, this can save considerable amount of computational time and cost.

7. Conclusion

This research develops a practical and scalable methodology for protection system screening of large scale transmission systems for planning studies to integrate offshore wind power plant projects. This methodology is verified using a 63,000-bus test system that represents the U.S. Eastern Interconnection. The results are very promising and show the effectiveness and application of the proposed methodology. The followings summarize the findings of this paper:

1. The more distant (electrically) the lines are from the POI the integration of the offshore wind power plant has less influence on their short-circuit currents.
2. The closer the lines are to a major inertia contributor generation unit the less influence the integration of offshore wind power plant has on their transient overvoltage.
3. The operation of SVC at the POI does not significantly contribute to the metrics associated with the system protection.
4. The results from two operational scenarios of 100% and 0% wind power generation sufficiently provide vital information to quantify its volatility.

This work considered the preliminary step for the short-circuit analysis to determine whether any upgrades are needed in protection system. The further research is required to acquire detailed results within the transient time frame, unbalanced faults, and for high frequency phenomena for which more advanced and specialized tools and methods are required. In addition, it is interesting to further explore the application of the presented method for power system security and contingency ranking and analysis studies.

Acknowledgment

This work has been supported by the U.S. Department of Energy under Grant No. DE-EE0005367: Great Lakes Offshore Wind: Utility and Regional Integration Study. The National Renewable Energy Laboratory's (NREL's) contribution to this work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with NREL.

The authors thank R. Kolacinski from the Case Western Reserve University and S. Barnes and R. D'Aquila from the GE Energy for their assistance.

References

- [1] A. Sajadi, K.A. Loparo, R. D'Aquila, K. Clark, J.G. Waligorski, S. Baker, Great Lakes Offshore Wind Project: Utility and Regional Integration Study, tech. rep., Case Western Reserve Univ., Cleveland, OH (United States), 2016.
- [2] J. Machowski, J. Bialek, J. Bumby, Power System Dynamics: Stability and Control, John Wiley & Sons, 2008.
- [3] P.M. Anderson, A.A. Fouad, Power System Control and Stability, John Wiley & Sons, 2003.
- [4] P.M. Anderson, Power System Protection, Wiley, 1998.
- [5] P.M. Anderson, Analysis of Faulted Power Systems, vol. 445, IEEE press Piscataway, 1995.
- [6] A.R. Bergen, Power Systems Analysis, Pearson Education India, 2009.
- [7] L. Meegahapola, D. Flynn, Impact on transient and frequency stability for a power system at very high wind penetration, in: Power and Energy Society General Meeting, 2010 IEEE, IEEE, 2010, pp. 1–8.
- [8] C. Eping, J. Stenzel, M. Pöller, H. Müller, Impact of large scale wind power on power system stability, in: Proceedings of the 5th International Workshop on Large-scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, 2005, pp. 1–9.
- [9] E. Muljadi, N. Samaan, V. Gevorgian, J. Li, S. Pasupulati, Short circuit current contribution for different wind turbine generator types, in: IEEE PES General Meeting, 2010 IEEE, IEEE, 2010, pp. 1–8.
- [10] S.M. Brahma, A.A. Girgis, Development of adaptive protection scheme for distribution systems with high penetration of distributed generation, IEEE Trans. Power Deliv. 19 (1) (2004) 56–63.
- [11] S.M. Brahma, Fault location in power distribution system with penetration of distributed generation, IEEE Trans. Power Deliv. 26 (3) (2011) 1545–1553.
- [12] Z. Akhtar, M.A. Saqib, Microgrids formed by renewable energy integration into power grids pose electrical protection challenges, Renew. Energy 99 (2016) 148–157.
- [13] L.V. Strezoski, M.D. Prica, Real-time short-circuit analysis of active distribution systems, in: 2016 IEEE Power and Energy Conference at Illinois (PECI), IEEE, 2016, pp. 1–8.
- [14] L. Strezoski, M. Prica, Calculation of relay currents in active weakly-meshed distribution systems, in: Clemson University Power System Conference, IEEE, 2016.
- [15] J. I. Marvik and H. G. Svendsen, "Analysis of grid faults in offshore wind farm with HVDC connection," Energy Procedia, vol. 35, pp. 81–90.
- [16] S.J. Haslam, P.A. Crossley, N. Jenkins, Design and evaluation of a wind farm protection relay, IEEE Proc. Gen. Trans. Distrib. 146 (1) (1999) 37–44.
- [17] J. Yang, Fault Analysis and Protection for Wind Power Generation Systems (PhD thesis), University of Glasgow, 2011.
- [18] O. Anaya-Lara, D. Campos-Gaona, E. Moreno-Goytia, G. Adam, Offshore wind farm protection, Offshore Wind Energy Gen. Control Protect. Integ. Electr. Systems (2014) 173–192.
- [19] L. He, C.-C. Liu, A. Pitto, D. Cirio, Distance protection of ac grid with HVDC-connected offshore wind generators, Power Deliv. IEEE Trans. 29 (2) (2014) 493–501.
- [20] D. Van Hertem, M. Ghandhari, Multi-terminal VSC HVDC for the european supergrid: Obstacles, Renew. Sustain. Energy Rev. 14 (9) (2010) 3156–3163.
- [21] J. Candelaria, J.-D. Park, VSC-HVDC system protection: a review of current methods, in: Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES, IEEE, 2011, pp. 1–7.
- [22] N. Miller, M. Shao, S. Pajic, R. D'Aquila, Eastern frequency response study, Contract 303 (2013) 275–3000.
- [23] N. Miller, M. Shao, S. Pajic, and R. D'Aquila, "Eastern Frequency Response Study," tech. rep., National Renewable Energy Laboratory (NREL), Golden, CO (United States).
- [24] N.W. Miller, W.W. Price, J.J. Sanchez-Gasca, Dynamic Modeling of Ge 1.5 and 3.6 Wind Turbine-generators, GE-Power systems energy consulting, 2003.
- [25] NERC, TPL-001-2 Standard - Transmission System Planning Performance Requirements, tech. rep., North American Electric Reliability Corporation (NERC), Atlanta, Georgia (United States), 2011.
- [26] IEEE, IEEE Guide for the Application of Transient Recovery Voltage, tech. rep., Institute of Electrical and Electronics Engineers (IEEE), New York City, NY (United States), 2011.
- [27] G. Andersson, Modelling and Analysis of Electric Power Systems Power Flow Analysis and Fault Analysis, EEH-Power Systems Laboratory, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland, 2004.
- [28] J. Machowski, J. Bialek, J.R. Bumby, Power System Dynamics and Stability, John Wiley & Sons, 1997.
- [29] E. Vittal, A. Keane, Identification of critical wind farm locations for improved stability and system planning, Power Systems IEEE Trans. 28 (3) (2013) 2950–2958.
- [30] S. Barnes, R. D'Aquila, B. Thomas, GE PSLF User Manual, tech. rep., General Electric (GE), Schenectady, New York, US, 2011.
- [31] S. Barnes, Progress Report - Great Lakes Offshore Wind: Utility and Regional Integration Study, tech. rep., General Electric (GE), Pittsburgh, Pennsylvania

- (United States), 2014.
- [32] L. Strezoski, M. Prica, K.A. Loparo, Generalized Δ -circuit concept for integration of distributed generators in online short-circuit calculations, *IEEE Trans. Power Syst.* 32 (4) (2017) 3237–3245. IEEE.
- [33] D.F. Howard, Short-circuit Currents in Wind-turbine Generator Networks (PhD thesis), Georgia Institute of Technology, 2013.
- [34] J.W. Group, et al., Fault Current Contribution from Wind Plants, 2015. Report to the T&D Committee of the IEEE Power and Energy Society, Pro Relay.
- [35] A. Sajadi, R. Kolacinski, K. Loparo, Transient voltage stability of offshore wind farms following faults on the collector system, in: *Power and Energy Conference at Illinois (PECI)*, 2016 IEEE, IEEE, 2016, pp. 1–5.