Renewable Energy 125 (2018) 225–233

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

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.

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), lxs533@case.edu (L. Strezoski), Kara.Clark@nrel.gov (K. Clark), mxp438@case.edu (M. Prica), kal4@case.edu (K.A. Loparo).

https://doi.org/10.1016/j.renene.2018.02.070
0960-1481/

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]:

$$\frac{d^2\delta_e}{dt^2} \approx \frac{P_{fault}}{H} \tag{1}$$

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.