Analysis and elimination method of the effects of cables on LVRT testing for offshore wind turbines

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Abstract. The current state, characteristics and necessity of the low voltage ride through (LVRT) on-site testing for grid-connected offshore wind turbines are introduced firstly. Then the effects of submarine cables on the LVRT testing are analysed based on the equivalent circuit of the testing system. A scheme for eliminating the effects of cables on the proposed LVRT testing method is presented. The specified voltage dips are guaranteed to be in compliance with the testing standards by adjusting the ratio between the current limiting impedance and short circuit impedance according to the steady voltage relationship derived from the equivalent circuit. Finally, simulation results demonstrate that the voltage dips at the high voltage side of wind turbine transformer satisfy the requirements of testing standards.

1. Introduction

Wind power is developing towards a mainstream, competitive and reliable power technology after the engineering practice during the last several decades. More than 54 GW of wind power were installed in 2016 and cumulative capacity increased by more than 12 percent to 486.8 GW, wherein offshore wind power reached 14384MW, according to the 2016 report of Global Wind Energy Council [1]. With the increasing penetration of wind power, the impacts on power system security and stability cannot be neglected, especially for the integrated offshore wind farm [2,3]. Therefore, wind turbines (WTs) are now required to keep connected during grid disturbances to support the power system.

In order to ensure the reliability of the grid-connected offshore WTs, low voltage ride through (LVRT) testing need to be performed deliberately. In terms of the LVRT testing, relevant research works including the LVRT testing theories and techniques have been carried out [4-6]. Up to now, most of the on-site LVRT tests performed by testing institutes and/or WT manufacturers are almost aiming at accessible WTs and the on-site testing for offshore WTs is just beginning [7,8]. With the fast development of offshore WTs, the on-site testing is essential because the testing conditions are the most realistic and the certified conclusions are convincing. In consideration of the harsh environment and difficulty of testing equipment transportation and installation, testing for offshore WTs is hard to be performed by transporting the equipment to the erected WTs as done for the onshore WTs [4,7,8].

Aiming to perform the LVRT testing for offshore WTs feasibly, cost-effectively and securely, this paper proposes an onshore testing method. That is to put the test equipment on the shore and generate voltage sags through submarine cables to the offshore WT under test. Due to the effects of submarine cables, the standard voltage sags generated by the testing equipment at the high voltage side of WT transformer will deviate from the required value. The effects of cables are analyzed firstly and a scheme eliminating effects of cables is presented. The voltage dip can be ensured at the required value.
according to the modification equation between the receiving and sending end of cables accurately. A case study of LVRT testing for offshore WTs is given to confirm the effectiveness of the proposed method. The methodology can be used to guide the LVRT testing for offshore WTs.

2. LVRT testing device and requirements for wind turbines

2.1. Voltage sag generating system for LVRT testing

The voltage sag generating system with adjustable inductors transported in a standard size shipping container is the only technology available to provide the LVRT testing service on-site, which is shown in figure 1 (a) [4]. During the test, the testing equipment is connected in series with the high voltage side of WT transformer. The specified symmetrical and unsymmetrical voltage sags can be generated by different configurations of current limiting inductor and short circuit inductor. The typical offshore wind farm consists of WTs, onshore or offshore substation and submarine cables. Most of the offshore wind farms are tens of kilometres from shore, so the LVRT testing for offshore WTs can be performed by putting the testing device on shore, as shown in figure 1 (b), and the required voltage dips can be imposed to the WT under test through cables. Therefore, there are no limitations as aforementioned but the standard voltage sags generated by the equipment may deviate from the specified values owing to the effects of cables. The effects of cables on LVRT testing are analysed in detail in Section 3.

2.2. LVRT testing requirements and procedure

The requirements of voltage sags and testing duration for WT are given in table 1. According to the testing codes requirements, the voltage curves should not surpass the prescribed area [5,6]. In other words, the voltage sag at the high voltage side of WT transformer should be ensured at the required values in case of making wrongly certified conclusions. During the test, the testing procedure is divided into three steps: 1) open the bypass switch \( S_1 \) to turn on the current limiting inductance \( X_{sr} \); 2) close switch \( S_2 \) to generate the voltage dip; 3) open \( S_2 \) and the voltage recovers.

| No. | Voltage sag depth (p.u.) | Fault time (ms) | Voltage sag waveform | No. | Voltage sag depth (p.u.) | Fault time (ms) | Voltage sag waveform |
|-----|-------------------------|----------------|----------------------|-----|-------------------------|----------------|----------------------|
| 1   | 0.90±0.05               | 2000±20        |                      | 4   | 0.35±0.05               | 920±20         |                      |
| 2   | 0.75±0.05               | 1705±20        |                      | 5   | 0.20±0.05               | 625±20         |                      |
| 3   | 0.50±0.05               | 1214±20        |                      |     |                         |                |                      |

3. Effects of cables on LVRT testing and its elimination method

3.1. Testing system modelling methodology

With the intent of analysing the effects of cables on the proposed LVRT testing method, the equivalent circuit of the testing system is presented at the beginning. According to the IEC 61400-21 standard, the voltage sag are set under no-load testing condition. Thus the elements concerned in LVRT testing include testing device, submarine cables and grid. The models of the submarine cables and testing
device applied in this paper are described in [3,4]. The grid is modelled as a voltage source connecting an impedance in series. The equivalent circuit of the testing system under no-load testing condition is shown in figure 2.

![Figure 2. Schematic of container-based LVRT testing.](image)

The parameters $Z$ and $Y_p$ of submarine cable shown in figure 2 are given as (1). $Z_c$ and $\gamma$ are the cable characteristic impedance and fundamental propagation constant. $l$ represents the length of cable.

$$
\begin{align*}
Z &= Z_c \sinh \gamma l \\
Y_p &= \frac{1}{Z_c} \frac{2(\cosh \gamma l - 1)}{\sinh \gamma l}
\end{align*}
$$

(1)

$Z_s$, $X_{sr}$ and $X_{sc}$ are the grid impedance, current-limiting impedance and short-circuit impedance respectively, $U_S$ and $U_{OWT}$ are the voltage of grid and high voltage side of WT transformer.

3.2. Analysis of effects of cables

According to the testing procedure, the effects of cables should be analysed during two time frames corresponding to the first two steps of test. During the first step only the current limiting inductor was turn on. Form figure 2, the steady voltage relationship between $U_S$ and $U_{OWT}$ is derived as (2).

$$
U_{OWT} = \frac{1}{U_S} \frac{1}{\frac{X_s + X_p}{Z_s} \sinh(\gamma l) + \cosh(\gamma l)}
$$

(2)

The deviation from the required voltage sag during the fault duration is represented by (3).

$$
U_{dev} = \left[ \frac{X_s + X_p}{Z_s} \frac{X_s + X_p + X_{sc}}{X_p} \cosh(\gamma l) \right] \left[ U_s \right]
$$

(3)

The simulation of (2) and (3) under different voltage sags are shown in figure 3.

![Figure 3. Effects of cables on LVRT testing.](image)

It can be seen from figure 3 (a) that the voltage difference between $U_S$ and $U_{OWT}$ increases with the increment of cable length. When there are only cables, the difference is less than 0.05 p.u., which can be ignored. With the increase of current limiting impedance, the voltage at the WT side will exceed the requirement of testing standards or even result in operation of WT relay. It’s the interaction between cables and current limiting impedance that affects the testing. As a consequence, wrong certified conclusions that the testing WT has no LVRT capability will be drawn. It can be observed
from figure 3 (b) that the voltage sag during faults are almost within the error tolerance (±5%) under the given conditions. The voltage difference can be eliminated by adjusting the values of $X_{sr}$ and $X_{sc}$.

3.3. Scheme for eliminating effects of cables on LVRT testing

The proposed scheme eliminating the effects of cables is to make use of a capacitor connecting in series with cables to compensate the current limiting impedance and cables impedance. The equivalent circuit of the proposed method is shown in figure 4.

$$\frac{U_{\text{w}}}{{U_S}} = \frac{1}{j(X_s + X_r) + Z_{\text{com}} \sinh(\gamma l) + \cosh(\gamma l)}$$

The difference between the actual voltage sag at WT side and required value is now expressed as

$$U_{\text{dev}} = \left| \frac{1}{j \left( \frac{X_s + X_r}{Z_c} + \frac{X_r}{Z_c^2} + X_r + X_{sc} \frac{Z_{\text{com}}}{Z_c} \sinh(\gamma l) + \frac{X_r}{X_{sc}} \cosh(\gamma l) \right)} \right| - X_{sr} \left| \frac{U_i}{U_i} \right|$$

Simulation of (4) and (5) under different voltage sags are performed and the results are shown in figure 5 (a) and (b) respectively. $Z_{\text{com}} = 2-j20 \ \Omega$ under the voltage sag of 0.9 p.u., $Z_{\text{com}} = 2-j50 \ \Omega$ under the voltage sag of 0.5 p.u. and 0.2 p.u.

4. Case study

In order to verify the effectiveness of the proposed method, time domain simulation are performed. Parameters of the testing device under different voltage sags and cables are given in [3,4]. The grid frequency is 50Hz, the concerned cable length is 40km and the grid impedance is 2 Ω. The values of $Z_{\text{com}}$ are given in Section 3.3. The simulation results under different voltage sags are shown in figure 6.
Figure 6. Equivalent circuit of the proposed method and simulation results.

It can be observed from figure 6 (a), (c) and (e) that overvoltage surpassing the requirements of testing codes occurs at the WT side when turning on the current limiting impedance, while the voltage sags are within the error tolerance. From figure 6 (b), (d) and (f), the overvoltage leading to failures of LVRT testing caused by cables are lowered to the required range when applying the proposed method.

5. Conclusions
The overvoltage affecting the LVRT testing are caused by the interaction between submarine cables and current limiting impedance of testing device. The voltage increases with the increment of cable length as well as current limiting impedance. The effects of cables can be eliminated and the voltage at the WT side can be ensured to be in accordance with the testing codes by the proposed method. The on-site LVRT testing can be performed successfully without environmental restrictions. The method proposed in this paper provides an effective technical option for offshore wind turbines LVRT testing.

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