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Harmonic background amplification in long asymmetrical high voltage cable systems

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ABSTRACT

This paper presents an analysis of a harmonic problem encountered on the Danish island of Anholt and its mitigation. Time synchronized power quality measurements are presented at transmission and island nodes. Harmonic phase gain factors are calculated from the transmission system to the island and a simulation model is constructed and used to explain the reason for the very high gain factors encountered. A resonance problem is identified and a recommendation is made for the use of phase-domain modelling for long asymmetrical cable systems. At the end of the paper, a harmonic filter design process is presented.

1. Introduction

Long cable systems at transmission level are becoming more and more common due to public resistance against the installation of new overhead lines (OHLs). The cable systems are used both as a part of the meshed electrical transmission infrastructure and also to form radial connections to single consumers or to production plants such as offshore wind power plants (WPPs). The electrical parameters of high voltage cables are significantly different from those of OHLs. This is especially true of the shunt capacitance, which can be 20–50 times higher on a high voltage cable compared to the equivalent-rated OHL. As a consequence, the system resonances tend to move to lower frequencies, introducing the potential for harmonic background amplification at these frequencies. The combination of the lower-order system harmonic resonances and the harmonic emissions from classical line-commutated hvdc current-source converters has proved to be a challenge in Denmark.

In 2012, the Anholt 400 MW offshore WPP was commissioned. In Denmark, Energinet.dk as the transmission system operator, owns and operates the high voltage cable export system, including the offshore WPP transformers. The Point of Connection (PoC) with the WPP asset owner is at the 33 kV busbars on the low voltage side of the WPP transformers. At the time of commissioning it was noticed that levels of 11th- and 13th-order harmonic voltage distortion close to the planning level were present at the PoC of the WPP.

Following a political decision in 2014, Energinet.dk took on responsibility for the electrical supply to the small Danish island of Anholt, situated off the east coast of Jutland. In order to ensure a cost-effective design, it was decided to connect the new 33 kV cable from the island to the 33 kV side of the Anholt WPP transformers. The geographical location of the Anholt WPP, Anholt island and the high voltage (220 kV) cable connection to the transmission grid can be seen in Fig. 1.

After the supply to the island was shifted from local generators to mainland supply, the local utility started receiving complaints from consumers on the island. A portable power quality monitoring unit was set up on the island to enable detection and identification of power quality problems related to harmonics.

2. System description

The transmission system connecting Anholt WPP consists of two 400 MVA transformers and three 220 kV cable parts: a 59.6 km cross-bonded land cable laid in flat formation; a 0.5 km beach cable; and a 24.5 km three-core submarine cable. A reactor station (GNK220) is located at the transition point between the land and beach cable. The offshore platform includes three 140 MVA, 220/33 kV transformers. The 33 kV array cable system used to

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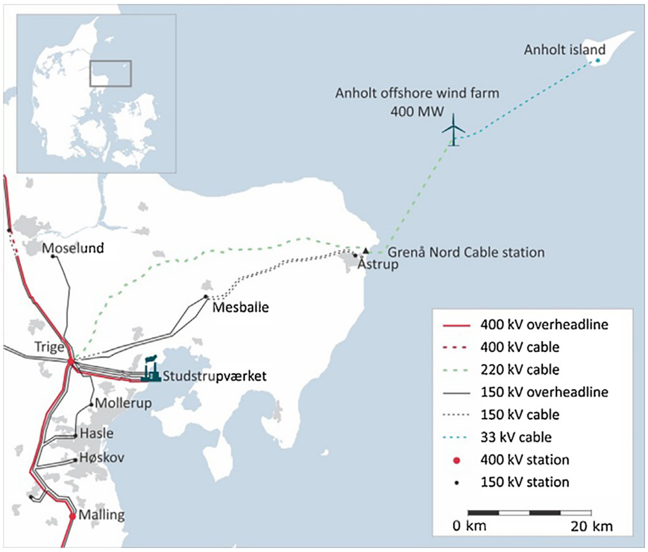

Fig. 1. Geographical location of the Anholt WPP and the island of Anholt.

connect the 111 Siemens 3.6 MW wind turbines to the offshore substation has a combined length of 152 km. A single line diagram of the electrical export system and the electrical connection to the island of Anholt is shown in Fig. 2.

At PoC#3 (see Fig. 2), a 27 km 33 kV cable connects to the island of Anholt. The cable is a three-phase 150 mm2 solid conductor aluminium cable with lead alloy sheaths and a common armour. A 33/15 kV 2 MVA transformer supplies the island, with the PoC with the local island utility located at the 15 kV busbars of the island transformer.

The demand on the island is strongly seasonal, varying from 0.2 MW during winter to 1.0 MW during the summer season.

3. Power quality measurement and analysis system

In order to identify the cause of the problem on the island, accurate high-bandwidth measurements are needed, both at the Trige 400 kV (TRI400) substation and on the island of Anholt (AHØ015). Traditional extra high voltage (EHV) instrument transformers are not capable of correctly representing all harmonic frequencies in their secondary circuits due to internal resonance in the measurement systems; this is true of capacitive voltage transformers (CVTs) at all but the fundamental harmonic order, and is true of electromagnetic wound voltage transformers (IVTs) beyond a certain frequency [1]. In recent years, specially designed transducers have been developed that can be retrofitted to traditional CVTs to provide a measuring unit with bandwidth well beyond the 50th harmonic [2]. Using these sensors with CVTs at TRI400, both the magnitudes and phase angles of the harmonics can be determined with good accuracy.

The IVTs at the 15 kV busbars on the island can accurately provide the magnitude of the harmonics in the high voltage signal for frequencies up to around 2000–3000 Hz [1]; no guarantee of accuracy is given for the harmonic phase angles. In this study, only measured harmonic magnitudes up to the 20th harmonic order are discussed and the 15 kV IVTs are therefore suitable for the harmonic measurements.

Statistical harmonic data is obtained using time synchronized commercially available “Class A” power quality meters as defined by IEC 61000 4 7 [3]. All statistical harmonics in this article are expressed as a percentage of the rms value of the fundamental frequency phase-to-ground voltage and given as 10-minute-aggregated values in accordance with IEC 61000 4 30 [4].

4. Analysis of harmonic background amplification

In order to identify the cause of the very high harmonic voltage distortion found on the island, the power quality measurements recorded at TRI400 and AHØ015 are analysed. The power quality measurements are recorded continuously over a period of 50 weeks. The highest 10 min IEC 61000-4-30 aggregated values (100th percentile) over that period are displayed from the 2nd to the 20th harmonic in Fig. 3 [4].

The harmonic content at transmission level in Denmark is dominated by the 11th and 13th harmonics, and this pattern is clearly present at Trige in Fig. 3. The highest 11th and 13th harmonic voltages recorded at TRI400 over the 50 weeks are 0.84% and 0.54% respectively. These harmonics are, therefore, properly managed. However, at the island, harmonic voltages at the 11th and 13th harmonic orders of 16.7% and 9.4% are measured. The time domain

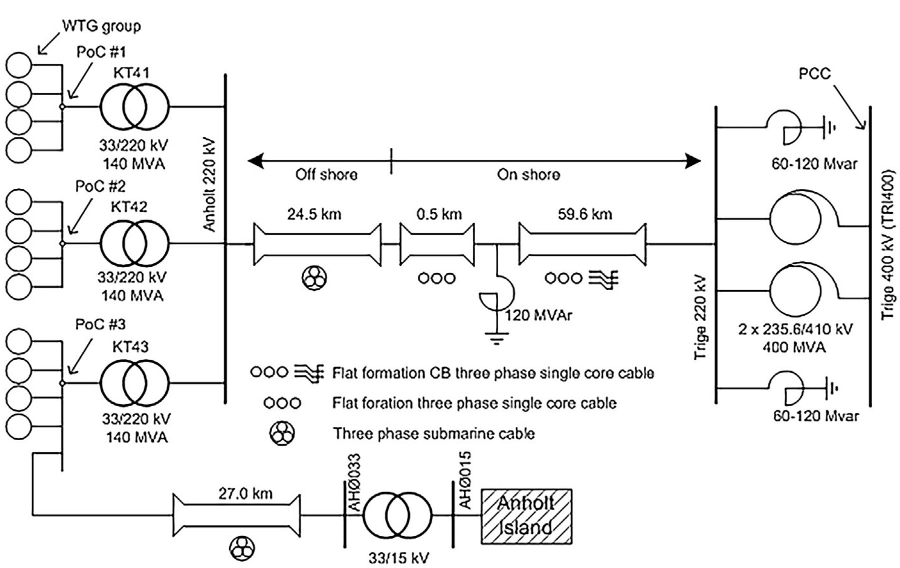

Fig. 2. Electrical export system and the electrical connection to the island of Anholt.