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Determination of voltage stress in case of operation of a hybrid HVAC/HVDC transmission line

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ABSTRACT

This paper is a study of the proposal to convert one of four 380 kV AC circuits on the same transmission line to a bipolar DC circuit with metallic return, using one of the three phase conductors. This study examines the voltage stresses and line insulation on the DC circuit.

1. Introduction

The fundamentals for voltage stress on a conductor installation for an HVDC transmission circuit converted from one of four 380 kV, 50 Hz AC transmission circuits on the same transmission tower structure are described in the following. The converters are expected to be voltage sourced converters (VSC) using the modular multi-level converter (MMC) in bipolar configuration with full bridge sub-modules. Voltage stresses on the DC line insulation is the main concern discussed in this paper along with impact of fundamental frequency coupling from the AC circuits to the DC circuit. MMC converters are selected for ease of line protection and increased power transfer capacity is the incentive for converting a circuit to DC technology.

2. Basis for DC design of hybrid transmission

Design and layout of a hybrid HVAC/HVDC overhead transmission line for this study is based on what was presented by Neumann et al. [1]. An example of a four circuit tower used for this study is shown in Fig. 1.

Line insulators for the DC circuit were assumed to be replaced with composite insulators with less weight than previously installed porcelain or glass cap and pin insulators. Conductors were unchanged and so the overall weight to the towers was considered unchanged.

For this study, a generic bipolar MMC converter is located at each end of the DC circuit with full bridge sub-modules. The question of a line reactor was examined. How two parallel MMC converters will be connected and controlled is open to further design since a reactor makes a difference to the results of the 50 Hz coupling studies. This difference is examined. For DC line faults, the full bridge MMC converter was controlled to do the protective function of reducing line volts to zero or near zero on the faulted pole to earth or to both poles if a pole to pole fault occurs.

Presently there is no standardized basis for hybrid AC–DC transmission systems. There has been no high voltage AC transmission lines converted to a DC circuit except for experimental purposes of one line in India.

3. Fundamental frequency coupling to DC circuit

Regarding HVDC interconnections, there are many successful schemes throughout the world, operating for over 40 years, some of which having overhead transmission lines sharing the same way-leave or right-of-way with AC transmission circuits where fundamental frequency coupling from the AC line to the DC line

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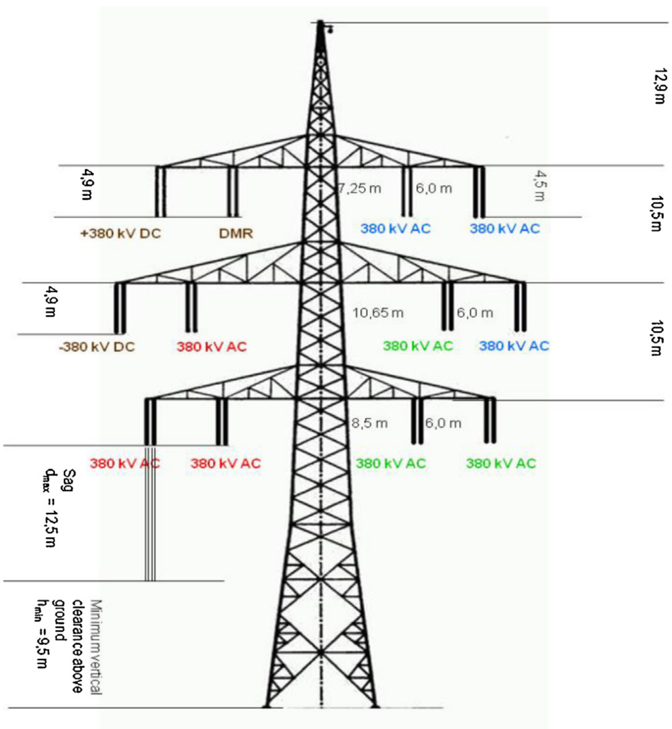

Fig. 1. Transmission structure for hybrid AC–DC transmission study of voltage stresses and fundamental frequency coupling to the DC circuit.

occurs. The one HVDC scheme where remediation was undertaken was the Hydro Quebec to New England HVDC transmission line where a fundamental frequency blocking filter was applied in the neutral end of each pole in the Sandy Pond converter [2].

Fundamental frequency coupling to a DC circuit with voltage sourced converters (VSC) has only recently been investigated [1,3,4].

The concern is that induced fundamental frequency currents will flow into the DC terminals of each of the VSC converters, causing reverse rectification, so that DC currents will flow through the converter side windings of the interface transformers for VSC converters. This, of course, can lead to saturation in the unit transformers, which is highly undesirable. Means to block the DC current from flowing into the interface transformers may be achieved by one or more of the following methods:

- Use of a fundamental-frequency-blocking filter in each pole in series with the pole converter. (These are used for the James Bay to Sandy Pond LCC transmission line.)
- Fully transpose the AC transmission lines that are coupling and superimposing AC fundamental frequency voltage and current on the DC circuit. (This is a real life case where transposition of the AC circuits is not practical on towers of Fig. 1.)
- Controls to the VSC converters that block DC current from entering or leaving the AC side terminals of the converters [5]
- Fundamental-frequency shunt filter across the DC terminals of the converter poles to bypass fundamental-frequency current away from entering the converter. Such a filter can be placed on the line side of line end reactor; tuned to 50 Hz to divert 50 Hz induced currents from entering the converter.

Elimination of the DC current through the interface transformers may not eliminate the superimposed fundamental-frequency voltage on the DC transmission line. If small, this may not be of much consequence. If large, then the DC voltage will have to be reduced so that the peak of the combined voltages stays at or below an acceptable level for the line insulation. This reduces the DC power level of the VSC transmission.

To avoid saturation of the unit transformer, the DC current passing through its valve side secondary windings must be reduced to about the same magnitude as the normal magnetizing current if the transformer is energized at no load from its secondary winding.

When fundamental-frequency coupling is present for a specific VSC transmission system, the technical specification for the converters must identify it adequately so that the equipment supplier can design and demonstrate an acceptable remedy.

For the hybrid AC–DC transmission line with a typical tower as shown in Fig. 1, there are a number of issues that impact the continuous peak voltage on the bipolar DC circuit. These are:

1. Whether the AC circuits are transposed.
2. If one AC circuit is out of service, particularly the top AC circuit on the opposite side of the tower the fundamental frequency coupling to the DC circuit is increased.
3. Use of fundamental frequency blocking filters in series with each pole, which blocks fundamental frequency current but the superimposed AC voltage may increase significantly.
4. The fundamental frequency coupled current superimposed on the DC current will increase as power flows increase on the AC circuits.

The stability of the MMC converters may be impacted by the fundamental frequency current superimposed on the DC current transformer saturation caused by DC current in the secondary windings of the interface transformer. Effort is required to ensure the VSC transmission controls are robust. Any adverse operation from saturation is avoided with VSC converter controls that eliminate the secondary winding DC current. Equipment suppliers will be able to develop a robust design but will need to do so with the coupled AC circuits represented in their design model.

With a hybrid AC–DC transmission line configured like shown in Fig. 1, a steady state fundamental frequency coupling study was undertaken with results presented in Table 1. The equivalent circuit diagram showing where the steady state coupling measurements were recorded from is shown in Fig. 2.

The frequency dependent phase based line model in the PSCAD library was used with all four circuits of 12 three conductor bundles and a mid-line tap 174 km from each end. Because the frequency on the line model was curve fitted over the frequency range of 0.5 Hz to 10,000 Hz, no adjustment was required for all steady state and transient studies undertaken. The circuits were studied with untransposed or with ideal transpositions.

Line voltage was most impacted at line centre and line current at converter poles at one end. PSCAD/EMTDC was used to represent the MMC converters and hybrid AC–DC transmission line. When transposed, the AC circuits were ideally transposed.

The MMC converters were based on the technique of Gnanarathna et al. [13] with further development for half bridge and full bridge sub-modules.

A number of important conclusions can be drawn for the results of Table 1. The superimposed AC voltage on the DC pole conductors due to mutual coupling from the AC circuits when blocking filters are applied will require the DC voltage level to reduce. This will in turn reduce the power transfer capability of the DC circuit.

Transpositions of the AC circuits are the most effective solution for reducing adverse mutual coupling effects but are costly and inconvenient. Without transpositions or fundamental frequency blocking filters, DC line end reactors have some effect on reducing fundamental frequency current into the converter poles without significantly increasing the AC voltage coupled to the DC lines.

The analysis of the results recorded in Table 1 present the need to determine how MMC converters can protect the secondary