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Analysis of half-wavelength transmission line under critical balanced faults: Voltage response and overvoltage mitigation procedure

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ABSTRACT

This paper presents a detailed study of half-wavelength (HWL) transmission line system under critical fault conditions. This non-conventional ultra high voltage alternating current (UHVAC) transmission line has excellent properties in steady-state operation condition and economic advantage when compared to conventional UHVAC system and even high voltage direct current (HVDC) transmission systems for similar power capacity. This technology has been studied for many decades and its response under condition fault is an important topic. First, the point of fault and the type of fault conditions are evaluated to confirm that balanced faults in specific regions are critical. Then the main characteristics of voltage response of HWL transmission system under balanced fault are presented and critical regions that produce severe overvoltage are identified and main transient characteristics are described. Finally, a preliminary mitigation procedure is shown and its performance is evaluated.

1. Introduction

Nowadays, large countries like Brazil, Russia and China require bulk power transmission projects to connect potential energy sources with load centers located at a long distance. Conventional ultra high voltage alternating current (UHVAC) transmission line projects could have lengths with more than 1000 km [1] and operate with more than 1000 kV [2] using intermediate substations. However, technical and economical constraints, such as the necessity of high reactive power support, stability issues and complex operational restrictions, limit this alternative for longer lengths. Cases with higher distances use ultra high voltage direct current (HVDC) transmission lines because of the great technological evolution in power electronics and many years of experience. Nevertheless, classical HVDC technology with line-commuted converters presents limitations, such as coarse reactive power control, necessity of dynamic reactive power support to work in weak power systems, necessity of very sophisticated control systems, among others [3,4].

An alternative for power transmission over long distance is a transmission line with half-wavelength (HWL) properties that is a point to point AC link. HWL line has been studied for many years [5,6] and now it raised attention for transmitting hydropower from the Amazon river basin to Southeast load centres of Brazil [7]; and transmitting power from Xinjiang region to Eastern coastal region of China [8].

HWL transmission line has a length equal to the half of wavelength of a system excited with a cosine function of 60 Hz that is around 2500 km, and for a 50 Hz system that is around 3000 km. It is possible to use its properties for flexible distance transmission trunks, considering tuning banks based on inductive and capacitive components [9,10].

Transmission lines with HWL properties allow to maintain the voltage at line ends near 1.0 pu independent of the loading level without additional reactive power support [6,11]. They have good steady-state stability properties, as it behaves as a short line [11] under normal operation. As HWL transmission lines do not use power electronics converters, the issues related to these equipments are not a concern. The switching transient overvoltage level on HWL lines are lower than those presented on conventional UHVAC lines using regular mitigation techniques [9]. Preliminary studies show that the cost can be much smaller than conventional UHVAC lines with similar power capacity and even lower than UHVDC transmission lines [12,13].

However, as HWL line is an outgoing technology, practical operational issues need thorough study. According with literature, protection system and critical faults along the line are the most important points to be approached.

In the field of protection system, many elements of conventional lines protection system cannot be directly applied to HWL line due to different behavior of line impedance and the necessity to consider the

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capacitance effect on such very long line [8,14]. Also, literature shows that phasor estimation during fault can require especial attention [15]. About these issues, some protection aspects are already being studied like: innovative impedance-base fault location algorithm [16,14] and faulty phase selector [17]. Other protection related fields like single-phase auto-reclosing scheme [18], single-phase overvoltage fluctuations [19] and voltage and current behavior under different fault types [20,21] are being studying.

About critical faults, previous studies show that some faults along the line can cause abnormal overvoltage level, especially for three-phase fault on critical HWL line regions, what indicates a positive resonance condition at network frequency [11]. Line-to-line (LL) fault will also promote severe overvoltages, as it will also generate positive (and negative) sequence resonance, and LL fault is much more prone to occur than three-phase faults, mainly considering that this bulk transmission will take advantage of compact transmission lines. These severe overvoltage jeopardize the line insulation level and also substation equipment, including the proper operation of protection equipment's as circuit-breakers [22].

Although three-phase faults are the least common type of fault in power systems, especially in UHVAC systems, they need special attention because critical fault locations can produce abnormal overvoltage on HWL lines and they represent the positive sequence response. The main properties can be directly extrapolated to LL faults.

In Ref. [23] surge arrester was considered to control those severe overvoltages due to critical faults and it was verified that an excessive quantity of these equipment would be necessary due to high energy produced during the fault. That would compromise the reliability and by far the most relevant property of HWL that is to be a point-to-point alternative.

This paper presents a detailed analysis of HWL line under faults. In Section 2, the test system is presented, and then a primary analysis of different fault types is shown in Section 3 to find the potential critical faults. After that, in Section 4 a detailed analysis of balanced faults and their critical conditions is shown, identifying the main factors associated to its severity, specifically fault type and location, the strength of remote terminal system and loading level. Such an extensive analysis has not been presented before. Finally, in Section 5 both sustained and transient study were performed and a preliminary mitigation procedure is proposed and tested. The criteria to locate and adjust the mitigation device are discussed.

2. Test system

2.1. HWL+ transmission line

Voltage level of 800 kV permit a good efficiency level for a HWL line with 2600 km [24]. Therefore, the test system considered for the present analysis is an 800 kV with 2600 km at 60 Hz transmission line that is a little more than half wavelength line. Such a long line needs a high nominal voltage level and it also should have high power capacity. In the present study the line bundle geometry was optimized to achieve SIL of 4745 MW [25]. This non-conventional line has an asymmetrical bundle configuration with different central phase geometry as shown in Fig. 1a, which additionally reduces the right of way. The position of each conductor in the bundle is shown in Table 1. The adopted soil resistivity is 2000 Ω m, what is a moderate value in Brazilian Amazon region [20,26]. Table 2 shows the electrical parameters for 60 Hz (considering a balanced line).

Actual transposition cycles were considered in the transient study. The 2600 km line was split into 9 transposition cycles of 288 km each one. Each cycle is divided into 4 sections of 48 km, 96 km, 96 km and 48 km. HWL+ line was implemented in PSCAD/EMTDC software with frequency dependent phase model.

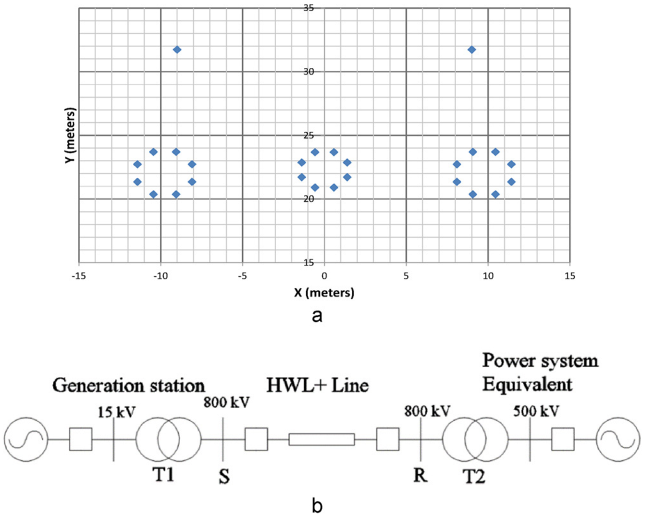

Fig. 1. Test HWL+ transmission system and power system connected at both ends.
(a) Tower geometry. Conductors with average height.
(b) Test power system.

Table 1
Position of the conductors in the bundle.

Phases	Phase A	Phase B	Phase C
1	−8.09; 22.73	1.39; 22.87	8.09; 21.35
2	−9.07; 23.7	0.58; 23.68	9.07; 20.37
3	−10.45; −23.7	−0.58; 23.68	10.45; 20.37
4	−11.42; 22.73	−1.39; 22.87	11.42; 21.35
5	−11.42; 21.35	−1.39; 21.72	11.42; 22.73
6	−10.45; 20.37	−0.58; 20.9	10.45; 23.7
7	−9.07; 20.37	0.58; 20.9	9.07; 23.7
8	−8.09; 21.35	1.39; 21.72	8.09; 22.73
Ground wires	−9; 31.73	9; 31.73	

Table 2
Transmission line parameters — calculated for 60 Hz.

Electrical parameters		
Zero sequence		
R0 (Ω/km)	X0 (Ω/km)	B0 (μs/km)
0.3871	1.3502	4.066
Positive/negative sequence		
R1 (Ω/km)	X1 (Ω/km)	B1 (μs/km)
0.0068	0.1737	9.5367
Electromagnetic parameters		
γ (km^{-1})	$\alpha + j\beta = 0.0000254 + j\, 0.0012873$	
Z_C (Ω)	134.98 − j 2.66	
P_C (MVA)	4745	
λ (km)	4882	

2.2. Equivalent power system

Different power systems are considered in order to identify their influence on the fault response. Specifically the following systems were considered: generation station, strong power system and weak power system.

The generation station has 11 synchronous machines and step-up transformers which resulted in three-phase short circuit current (Scc) at 800 kV busbar of 9.6 kA.

The strong and weak power systems were based on typical 500 kV Brazilian data, specifically: 40 kA (strong system) and 10 kA (weak system). To calculate the positive sequence and zero sequence