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Large amplitude vibrations of long-span transmission lines with bundled conductors in gusty wind

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ABSTRACT

Large amplitude wind-induced vibrations of ice-accreted/unaccreted conductors in overhead transmission lines are frequently observed in the field. Damage due to the large vibrations is costly and affects many aspects of modern society. In this study, an attempt is made to identify the large amplitude gust responses and to distinguish them from the unstable phenomena of galloping in field-observed vibrations of long-span-overhead transmission lines that have bundled conductors. An extensive method of combining field-measured data analysis, eigenvalue analysis and gust response analysis is applied. The field-measured wind and vibration characteristics and their relations are first discussed to study preliminarily the types of field-measured responses. Next, the natural frequencies and mode shapes of the transmission lines are estimated by eigenvalue analysis using reliably created finite element models to verify the field-measured response characteristics in the frequency domain. Gust response analysis is finally conducted to interpret intensively the large-amplitude gust responses of overhead conductors, and results in good agreement with field-measured vibrations. Through this extensive study, it is concluded that most of the field-measured responses are gust-type vibrations and that a gust response can be sufficiently large to cause damage in the overhead transmission lines, regardless of their type.

1. Introduction

When considering the causes of large-amplitude wind-induced vibrations, people often think that such vibrations in overhead transmission lines are caused by a galloping unstable phenomenon, which was first identified and explained by Den Hartog (1932). This galloping phenomenon, which is characterised as a low-frequency, large-amplitude, wind-induced vibration with a self-excitation mechanism, usually occurs in moderately strong and steady wind, while its incidence is rather infrequent and unpredictable under conditions in which there is an interaction of the wind and asymmetrical ice or wet snow accreted conductors. The galloping phenomenon is well recognised as one of the major wind-induced vibrations that causes damage in transmission lines. Phase-to-phase flashovers can occur and lead to widespread electrical power outages. Large amplitude vibrations of conductors can cause overload on towers and fatigue damage to hardware as well as insulators and conductors. The galloping phenomenon is one of the classical problems in overhead transmission lines under certain climatic conditions. It has been studied by many researchers through field observations (Yukino et al., 1995; Diana et al., 1990; Rawlins, 1981), wind tunnel experiments (Keutgen and Lilien, 2000; Nakamura, 1980; Novak and Tanaka, 1974; Nigol and Buchan, 1981a), and numerical analyses (Yamaguchi et al. 1995; Desai et al., 1995; Ohkuma and Marukawa, 1999). Furthermore, there has been extensive research on the identification of the galloping mechanism (Nigol and Buchan, 1981b; Wang and Lilien, 1998; Blevins and Iwan, 1974; Nakamura, 1980) and its prevention through different devices (Havard and Pohlman, 1979; Hunt and Richards, 1969; Richardson, 1965). An excellent survey of the state-of-the-art on galloping unstable phenomena is given in the technical brochure (CIGRÉ, 2005).

Since Den Hartog's finding of the galloping phenomenon, any large amplitude wind-induced vibration is generally thought to be caused by the galloping unstable mechanism. However, a so-called gust response that is a randomly forced vibration in gusty wind can be another source of large amplitude wind-induced vibrations in overhead transmission line conductors (Yamaguchi et al., 1995). Because of the high level of flexibility in the transmission lines, the possibility of a large amplitude random response due to atmospheric gusty wind cannot be overlooked; this phenomenon is shown in the relevant numerical analysis (Ohkuma and Marukawa, 1999). It is also confirmed by the analysis of field-measured data (Gurung et al., 2003; Gull et al., 2011) which shows that besides the galloping, the occurrence of a large-amplitude gust response is not only in the horizontal direction but also in the

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vertical direction. With regard to the computational modelling of gusty wind-transmission line conductor interactions, a refined computational model of the conductor in the surrounding moving air is used to investigate the dynamic interaction between the wind and the conductor motion (Keyhan et al., 2013). In the computational model, wind load time histories are used as input for nonlinear dynamic analysis, with the direct time integration of incremental equations of motion. In consideration of the nonlinear dynamic response of transmission line conductors that were subjected to gusty wind in arbitrary directions, a formulation and computing procedure has been proposed and introduced. In the computational modelling, the exact static equilibrium configuration according to the elastic catenary equation under self-weight, non-levelled supports, arbitrary sag, large displacement and deformation fields have been considered (Impollonia et al., 2011; Miguel et al., 2012; Keyhan et al., 2013). Most of the references emphasised the computational methods for the transmission line-imposed wind force interaction in time domain, without interpreting the characteristics of the large amplitude gusty wind-induced vibration and validating the methods by full-scale vibration measurements.

Despite such numerous field observations, studies and applications on the large amplitude wind-induced vibrations for more than a half century, a practical protection method that is recognised as fully reliable has not yet been developed. A minimisation or control method for wind-induced vibrations of transmission lines still depends on a field trial-and-error procedure (Ohkuma and Marukawa, 1999; CIGRÉ, 2005). Accidents such as the loosening of bolts and the breaking of insulator attachments, spacers, and porcelain plates due to the large amplitude vibrations of iced/un-iced transmission line conductors in gusty winds have been observed even recently by Tokyo Electric Power Company (TEPCO). For the rational design of overhead transmission lines and their smooth operation, some measure for controlling both the galloping and the gust response is necessary. However, because the characteristics of the galloping and gust response are entirely different, the methods for minimising or controlling them would be different. It is, therefore, indispensable to identify galloping and gust responses separately.

In this study, an extensive method that consists of field-measured data analysis, eigenvalue analysis and gust response analysis based on the finite element (FE) model is applied to fully identify and interpret the characteristics of large amplitude gust responses that were observed in long-span, overhead transmission lines that have bundled conductors. The field-measured wind and displacement characteristics, such as the mean wind velocity, wind direction, turbulence intensity, root mean square (RMS) and power spectral density (PSD) of the wind velocity and response displacement, are first discussed, to have an initial idea of the type of field-measured vibrations. Next, eigenvalue analysis is performed to evaluate the response spectral peaks followed by the gust response analysis in the frequency domain. From the gust response analysis, the response PSDs and the RMS responses are obtained for the measured wind characteristics and are compared with the field-measured PSDs and RMS responses, to ascertain the type of field-observed vibrations in different types of transmission lines.

2. Outlines of transmission lines and field measurements

TEPCO has been recording wind-induced vibrations of its overhead transmission lines with multiple bundled conductors, both in iced and un-iced conditions. In the present study, the vibration data with the wind data recorded by TEPCO is analysed for three different types of long-span transmission lines, which were selected because some damage was reported in different components of these transmission lines due to large wind-induced vibrations. The maximum peak-to-peak amplitudes (MPPAs) are observed, for example, at approximately 7 m in the horizontal direction, 5 m in the vertical direction and 70° in the torsional direction. Such large span vibrations can result in the dynamic response of components such as insulators, spacers, and jumpers, which can lead to damage. Therefore, objectives for the field measurements were set to identify clearly the causes of large amplitude vibrations that could have caused damage in different components of the transmission lines.

Fig. 1 (a), (b) and (c) show the geometries of the studied transmission lines, Line A, Line B and Line C, respectively, with the instrumentation for the field measurements. Line A has eight bundled conductors in a single dead-end span of 615 m between two anchoring towers, No. 58 and No. 59, with a 40 m difference in their levels. Line B has four bundled conductors in two spans: a 624 m span between the towers No. 3 and No. 4, and a 407 m span between towers No. 4 and No. 5. The level differences of two anchoring points in the first and second spans are 137 m and 51.6 m, respectively. The two spans are not aligned, and they have an acute angle of 8°58′, as shown in Fig. 1(b). It should be emphasised that Line B is anchored at the intermediate tower and is connected through a jumper line, which can change the dynamic characteristics of the transmission line system. Line C has two bundled conductors in three spans: a 249 m span between towers No. 36 and No. 37, a 439 m span between towers No. 37 and No. 38, and a 421 m span between towers No. 38 and No. 39. The level differences of the anchoring/suspending points in the first, second and third spans are 82.7 m, 59.7 m and 109.8 m, respectively. In Line C, suspension-type insulators are used for the intermediate towers. The specifications of lines A, B, and C are given in Table 1.

The accelerations in all three translational directions and the angular velocity were measured by using accelerometers and angular velocimeters, respectively, at the quarter- and mid-spans, as shown in Fig. 1, for observing wind-induced vibrations that were dominated by symmetric and anti-symmetric lower-frequency modes in up to three-loop modes. For higher-frequency anti-symmetric modes,

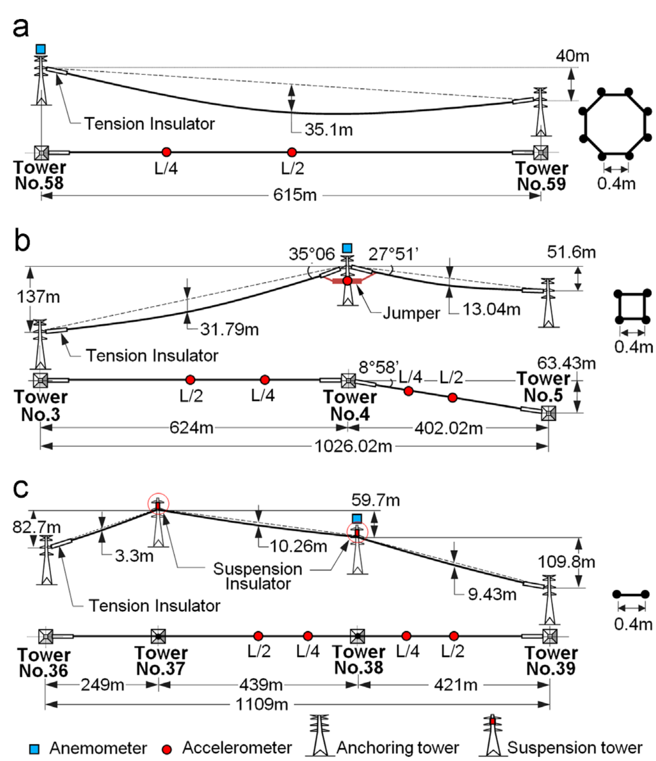

Fig. 1. Geometries of the transmission lines and cross sections of bundle conductors: (a) Line A; (b) Line B; and (c) Line C.