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EPSR-5011; No. of Pages 7
ARTICLE IN PRESS
Electric Power Systems Research xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Electric Power Systems Research
journal homepage: www.elsevier.com/locate/epsr

Effect of a lossy dispersive ground on lightning overvoltages transferred to the low-voltage side of a single-phase distribution transformer

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ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 25 October 2016
Accepted 4 January 2017
Available online xxx

Keywords:
Lightning
Frequency-dependent ground parameters
Wideband transformer model
Transferred voltages
Transmission lines

ABSTRACT

This paper presents a study of lightning overvoltages transferred to the low-voltage side of a 10 kVA 7.967 kV/240–120 V single-phase distribution transformer considering dispersive ground effects in the medium-voltage distribution line terminated at its primary side. A two-port wideband model that is capable to represent the transformer behavior under different load conditions is considered. The medium-voltage distribution line is modeled using Marti's transmission line model modified to include the variation with frequency of the ground resistivity and permittivity. Periodical grounding points are also modeled considering dispersive ground effects. Phase-neutral voltages transferred to the transformer secondary are calculated for direct lightning strikes at the medium-voltage line including insulation breakdown, surge arresters, and different load conditions. It is shown that the frequency variation of the ground resistivity and permittivity can significantly affect voltages transferred to the low-voltage side of the transformer if a high-resistivity soil is considered, depending on load conditions and on flashover occurrence. It is also shown that the importance of considering or neglecting frequency-dependent ground parameters on lightning overvoltages transferred to the secondary side of the transformer is minimized by the installation of a medium-voltage surge arrester at its primary side.

1. Introduction

Many studies have been presented in recent years to include the variation with frequency of the ground resistivity and permittivity in the calculation of power system transients (e.g., [1–10]). There seems to be a consensus that such variation should not be neglected if high-frequency transients are to be analyzed in the presence of a poorly-conducting ground. However, most of the existing studies deal with relatively simple line topologies. As a consequence, it is sometimes difficult to extend the obtained results to more representative cases. This suggests that additional efforts are necessary to clarify the effect of the frequency variation of the ground parameters in the calculation of power system transients, especially in the case of distribution lines, which are inherently complex.

In this paper, an attempt is made to investigate the influence of a lossy dispersive ground on the calculation of phase-neutral voltages transferred to the low-voltage side of a single-phase distribution transformer with center-tapped secondary. The transformer is located at the end of a medium-voltage distribution line with multiple grounding points that is subjected to direct lightning strikes at different locations. The analysis is performed assuming the connection of different resistive loads at the low-voltage side of the transformer, which is represented as a two-port wideband model that is valid under different load conditions. The study also investigates the influence of insulation breakdown at the medium-voltage line and of a surge arrester protecting the primary side of the transformer on the transferred voltages.

This paper is organized as follows. Section 2 discusses the proposed transformer model and presents its validation for different load conditions. Section 3 presents the studied case in detail and describes the models used in simulations in the Alternative Transients Program (ATP) [11]. Section 4 illustrates the influence of different parameters on phase-neutral voltages transferred to the low-voltage side of the transformer. Conclusions are presented in Section 5.

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http://dx.doi.org/10.1016/j.epsr.2017.01.009
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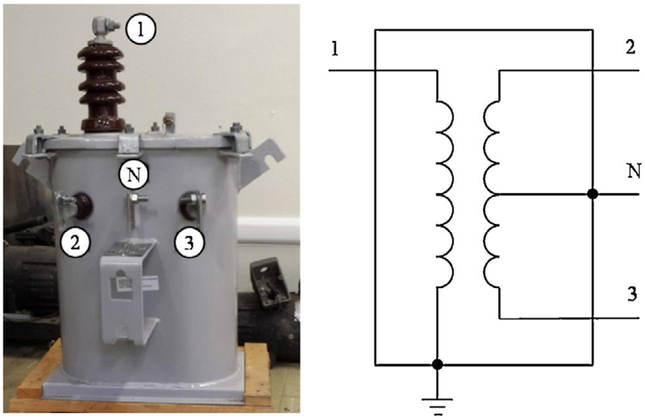

Fig. 1. Single-phase distribution transformer with center-tapped secondary.

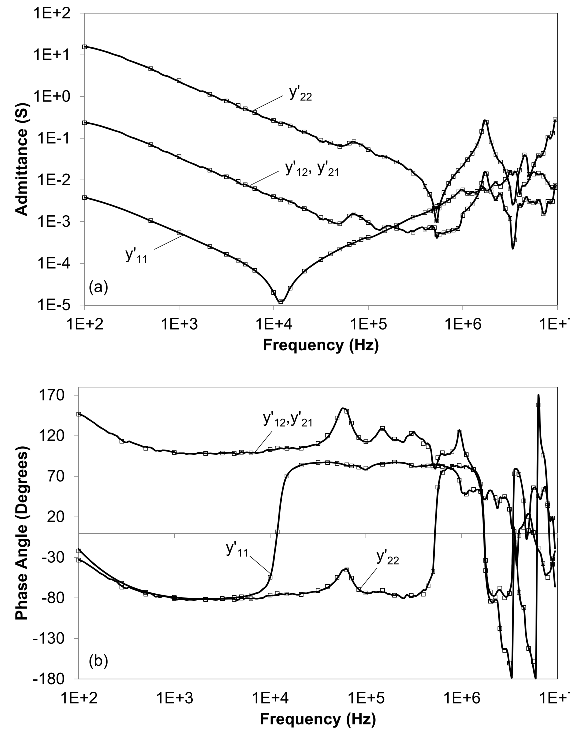

Fig. 2. Magnitude and phase angle of the measured (black solid lines) and fitted (square dots) admittance terms of (1).

2. Transformer model

2.1. Theoretical basis

The single-phase transformer considered in this study is a 10 kVA 7.967 kV/240–120 V transformer with center-tapped secondary that is widely used in distribution networks in Brazil (see Fig. 1). It has four available terminals: one neutral terminal (labeled as N in Fig. 1), which is solidly grounded and connected to the transformer tank, one high-voltage terminal (labeled as 1), and two low-voltage terminals (labeled as 2 and 3) with symmetrical voltages with respect to the neutral. A wideband model can be obtained for this transformer by measuring the elements of its admittance matrix Y in a wide frequency range. By taking the neutral as the common ground reference, Y is a 3×3 symmetric matrix that relates the terminal voltages represented by vector V, of order 3×1, to the currents entering these terminals, represented by vector I, also of order 3×1. To obtain all elements of Y a total of nine measurements must therefore be performed at each frequency of interest [12].

To reduce the amount of required measurements, a simplified two-port model that assumes terminal 3 to be left permanently open (no load condition) is considered for the transformer illustrated in Fig. 1. Using symmetry considerations, it is possible to write [13]

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} y'_{11} & y'_{12} \\ y'_{21} & y'_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} y_{11} - y_{22}t_{21o}^2(1+t_{23})^2 & -y_{22}t_{21o}\left(1-t_{23}^2\right) \\ -y_{22}t_{21o}\left(1-t_{23}^2\right) & y_{22}\left(1-t_{23}^2\right) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad (1)$$

where y_{11} and y_{22} are the admittances obtained by applying a sinusoidal voltage at terminals 1 and 2, respectively, and measuring the resulting current/voltage relationship while all the remaining terminals are short-circuited to ground. Element t_{21o} is the ratio between voltages at terminals 2 and 1 for the application of a sinusoidal voltage at terminal 1 assuming terminal 3 open. Finally, element t_{23} is the ratio between voltages at terminals 2 and 3 for the application of a sinusoidal voltage at terminal 3 assuming terminal 1 to be short-circuited in the frequency range of interest. The determination of (1) therefore requires four different measurements at each frequency: one to determine y_{11}, and three others to determine y_{22}, t_{21o} and t_{23}. This requires substantially less work compared to the measurement of the nine elements of Y at each frequency.

2.2. Parameter determination

Fig. 2 illustrates the measured magnitudes and phase angles of y'_{11}, y'_{21}, and y'_{22} in Eq. (1) from 100 Hz to 10 MHz, which were obtained for the application of 10 V sinusoidal voltages at the transformer's terminals. Fig. 2 also illustrates the fitted magnitude and phase angle curves obtained assuming a single set of 80 complex poles to represent all matrix elements in the vector fitting technique [14]. It is seen that the agreement between measured and fitted data is very good.

2.3. Model validation

To validate the transformer model, laboratory tests were performed with the application of 10 V step voltages at terminal 1 and the measurement of the voltages transferred to terminal 2 with terminal 3 permanently open. Four different resistive load conditions were assumed at terminal 2: $R = \infty$, $R = 470\,\Omega$, $R = 47\,\Omega$, and $R = 4.7\,\Omega$. The transformer model was implemented in ATP as a network of linear elements as proposed in [15]. Comparisons between measured and calculated voltages at terminal 2 are shown in Fig. 4. A very good agreement is observed, which indicates the accuracy of the proposed transformer model. It is also observed that in none of the cases the peak value of the transferred voltages exceeded 6% of the applied step voltage amplitudes.

3. Study of transferred lightning overvoltages

3.1. Simulated case

The simulated case corresponds to a distribution line with two vertically-stacked aluminum wires, both with radius of 0.85 cm, located at heights of 8.4 m (phase conductor) and 7.2 m (neutral) above the ground. The line is matched at the left end and extends