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Transient analysis of inductive induced voltage between power line and nearby pipeline ☆

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ABSTRACT

Among the available literature on electromagnetic interference between high voltage power lines and nearby pipelines, the topic of transient induced voltage on the pipelines are rarely discussed. Fault in high voltage transmission systems is usually cleared in several cycles, sometimes even before the fault current reaches the steady state. This paper proposes an analytical approach for calculating the transient induced voltage and current on a pipeline due to inductive coupling using a circuit model. A numerical example is studied to demonstrate the waveforms of transient induced voltage and current on the pipeline. Simulation results show that the transient peak of the induced voltage is greater than steady state values. Therefore, it is necessary to study the induced voltage and current during the transient period.

Introduction

The issue of AC interference between high voltage power lines and nearby pipelines has been a topic of interest since the early 1960s. In recent years, increasing energy consumption has led to higher loads and short-circuit current levels occurring simultaneously. Moreover, the ever-increasing cost of rights-of-way has resulted in the fact that power lines and pipelines often share a common corridor. Thus increases the interference problems substantially.

Starting from 1976, IIT Research Institute (IITRI) has evaluated the voltages induced on gas pipelines located within a 60 Hz AC transmission lines corridor. In subsequent years, a method was developed to predict the induced voltage on a pipeline using Thevenin equivalent circuits [1,2]. In late 80s, a computer program named Electromagnetic and Conductive Coupling Analysis from Power lines to Pipelines (ECCAPP) [3–5] was developed for accurately simulating the realistic complex right-of-way problems and investigating the effects of various system parameters.

A pipeline is divided into short segments, which are then modeled with T-elements with lumped self-impedances and admittance. However, the number of segments required to model the pipeline is usually too large and that imposes an unnecessary burden on computation. Djogo and Salama [6] proposed a new method, which reduced the number of sections for establishing the pipeline model. The method was based on the lossy transmission line model for buried conductors, but was modified by abandoning the Thevenin circuit representation of pipeline sections and by introducing a four-pole equivalent π circuit of a pipeline section. The problem of coupling to multiple parallel pipelines was also analyzed utilizing the model method. The paper also provides a way to deal with the non-parallel situation by dividing the pipeline sections into small segments.

Amer [7] used the Line and Cable Constant (LCC) module in EMTP to analyze the inductive interference generated by 132 kV overhead transmission line on metallic pipelines under different fault types. This study showed that three-phase to ground fault gave the least induced voltage along the pipeline due to its symmetry. The single-line-to-ground fault, however, provided the worst results.

Isogai and Ametani [9] analyzed the effect of power line configuration on induced voltage. The results showed that with the same line and ground parameters, the horizontal three-phase line configuration tended to induce higher voltages on the pipelines than vertical line configuration. Also, the voltage

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induced by a twin-circuit line is less than that induced by a single-circuit line.

Finite element method (FEM) has been utilized for solving AC interference problems in [11–13]. In [12], the authors studied a case where a pipeline had defects on its coating. These defects were modeled as a collection of leakage resistances that were distributed along the pipeline, and that acted as mitigation grounding. Rigorously, model the complete network needs a 3-D FEM. However, because the shared corridor is typically tens of miles, solving for the entire corridor would require too much computation. The same group of researchers later proposed a hybrid method [13], utilizing both 2-D FEM and the circuit approach, in which the mutual impedances between the pipeline and the transmission line were calculated by FEM, while the induced voltage and current distribution were computed by the circuit approach.

Despite the extensive studies on the topic, the analysis on transient induced voltage is still missing. As the network is inductive, the transient fault current could be much higher than the steady state fault current. Therefore, it is necessary to study the induced voltage and current during the transient period. However, among the literature in this area, only few briefly discuss this topic. The only references that can be found are [8,10]. In [8], the author used current distribution, electromagnetic fields, grounding and a soil structure analysis (CDEGS) software package to analyze the response of the pipelines to transmission line lightning and switching transient. Fault current was first calculated at multiple frequencies in time domain, and then transformed to frequency domain to generate a frequency spectrum using Fast Fourier Transform (FFT). After the frequency spectrum was formed, the time domain response can be obtained by taking the inverse FFT. This method, however, is computationally very heavy, and the results are not truly the transient response, but the steady state response, when the fault is not cleared. A recently research [19] uses the CDEGS package to simulate the induced voltage and current on a de-energized transmission line adjacent to energized circuits. However, it is still limited to the steady-state calculation.

The authors in [10] presented another approach based on iterative Finite Different Time Domain (FDTD) method. First, the voltage and current along the pipelines were discretized to a series of points using first order central difference formula; then an iterative formula was obtained for both voltage and current using recursive convolution. However, the fact that each tower can be grounded was not considered in this model. The LCC module in EMTP can simulate the transient phenomenon, but it can only handle the situation where both the conductors are bare and over ground. It is impractical to draw so many LCC modules in EMTP interface if the parallel corridor is long.

This paper proposes an analytical approach for calculating the transient induced voltage and current on a pipeline due to inductive coupling using a circuit model. This method is easy to program and requires only modest computer memory. The rest of the paper is organized as follows: The circuit representation of the power line and pipeline system is demonstrated in section 'System modeling', in which differential circuit equations are formulated. A numerical example showing the transient induced voltage and current waveform is shown in section 'Case study'. Conclusions are drawn in section 'Conclusions'.

System modeling

The circuit approach and the field approach are two basic models commonly used in the literature for system modeling. The circuit approach is based on the circuit theory, straightforward but it has limited ability to analyze conductive coupling. The field approach, on the other hand, is based on the electromagnetic field theory, with which the capacitive, inductive and conductive coupling are considered together. The field approach requires numerical methods such as FEM to solve. However, field approach cannot perform transient analysis. The method proposed in this paper is based on the circuit approach, which treats the power line system and pipeline system as two individual circuit networks coupled with a magnetic field. A complete circuit model is built for the power line-pipeline system using Kirchhoff's Law. The modeling of the system is discussed next.

Circuit representation

Neglecting the high frequency components, the transmission line system and pipeline system can be equivalent to two circuit networks represented by resistance and inductance. The idea is to set up a state space representation. By doing that, the circuit representation for each system is described as follow.

Transmission line

A typical 500 kV transmission line system consists of three bundled phase conductors, two overhead ground wires and supporting lattice towers. The overhead ground wires are usually continuously connected to the supporting tower and grounded so that when a fault occurs, the fault current flows in the ground wires can be diverted to the grounding system through towers. During normal operation, the three-phase of the transmission line are supplied with a balanced current; additionally, the loads at the end of the line are balanced. The equivalent circuit representation for the transmission line system during normal operation is represented in Fig. 1.

In Fig. 1, the phase conductors are connected to the load and supplied by a three-phase voltage source. In a real power system, the transmission lines are always connected in the network, which means they have multiple sources and loads. However, here we are most concerned with the current in the line. For simplicity, the transmission line is only modeled as a radial connected system with a single source and single load. The two overhead ground wires are replaced by a metallic return path, with the line impedance cut one half as shown in Fig. 2. The series impedances of the conductors are divided into N sections according to the tower span, where each section has self and mutual impedances. The series impedances for phase conductors and ground wires are represented by $R_a + j\omega L_a$ and $R_g + j\omega L_g$, where subscript a and g denote phase conductor and ground wire, respectively. The mutual impedance is represented by $R_m + j\omega L_m$, and the source impedance of the system is $R_s + j\omega L_s$. All the towers are grounded with resistance R_t (R_t may vary for each tower). The three-phase voltages sources are represented by e_A, e_B and e_C, and currents by i_A, i_B and i_C. The circuit equation for each mesh can be written by applying

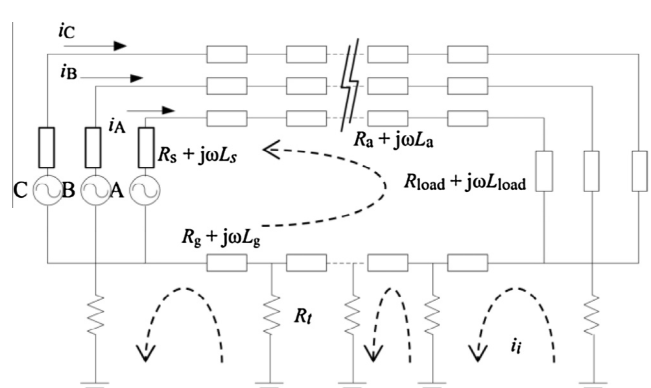

Fig. 1. Circuit representation of transmission line system during normal operation.