Induced Voltages on Long Aerial and Buried Pipelines Due to Transmission Line Transients

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***Abstract*—In a previous paper [1], the voltage induced onto a 1-km above-ground pipeline by transmission line transients was shown to be significant in comparison to the induced voltage resulting from power system currents. This paper enhances the previous work in three distinct areas. First, both aerial and buried pipelines are considered. Above-ground pipelines are shown to be more at risk from transient-induced voltages. Second, parallelisms of up to 10 km are simulated. The results show that increasing parallelisms do not result in higher induced voltages once a critical distance has been reached. Third, a backflashover from a tower in the vicinity to a pipeline is modeled. This allows conductive coupling to take place at the same time as inductive and capacitive coupling. Backflashovers are shown to be an important consideration in determining the maximum voltages observed on a nearby pipeline.**

***Index Terms*—Lightning, pipelines, switching transients, transmission lines.**

I. Introduction

IT IS COMMON practice to consider the electromagnetic coupling of parallel transmission lines and pipelines during steady-state and faulted operation of the power system to ensure unsafe or damaging voltages are not present on the pipeline. All pipelines or other metallic structures running parallel to alternating current (ac) transmission lines are subject to interference arising from inductive, capacitive and resistive coupling.

Inductive coupling arises when the pipeline is placed in a time-varying magnetic field. The voltage found at the pipeline ends will vary linearly as a function of length of parallelism for cases where the pipeline is well coated (i.e., has a high resistance to earth) and will vary according to soil resistivity. Pipelines above and below ground are both affected by inductive coupling. When the transmission line is operating in a normal condition, the electromagnetic fields produced by the three overhead line phases generally balance each other and significantly reduce the net field seen by the pipeline. This is not the case when an asymmetrical fault is present on the power system and flows are not uniform. When the imbalance of the three phase electromagnetic field and the higher magnitudes of fault current flows are considered, it becomes obvious that much higher pipeline voltages can be produced.

Capacitive coupling only affects pipelines located above ground since these have a capacitance to both the transmission line and to earth. They, therefore, effectively act as potential dividers. In this case, there is no variation of induced voltage with length. Generally, capacitive coupling is a secondary effect in terms of the total voltage induced on a pipeline with any significant amount of parallelism to an overhead line. Pipelines buried below ground are shielded from the electric field produced by the transmission line and cannot be affected by capacitive coupling.

Resistive coupling between a transmission line and a pipeline is only relevant during ground faults when significant levels of current flow into the ground. For example, if a phase-to-ground fault takes place at an overhead line tower close to the pipeline, the potential at the base of the tower will rise as will that of the surrounding ground. This, in conjunction with the high level of inductive coupling that takes place in this situation, puts the pipeline at severe risk.

There are three main reasons for being concerned about the rise in the potential of a pipeline. First, any person touching a pipeline that is subject to the influence of a high voltage transmission line may be at risk of electric shock. For this reason, maximum allowable levels of steady state-induced voltage are generally imposed on pipelines. These maximum levels vary from country to country but typically are in the order of 50 V (although values as low as 10 V exist). Similar restrictions exist concerning the maximum voltage that can be present on a pipeline during a power system fault. The allowable voltage during the flow of power system frequency fault current is typically between 300 and 1500 V [2].

These values of voltage are based on safe levels of current that can be tolerated by the human body and the impedance of the current path. Higher voltages would be tolerable when making contact with coated pipelines as the coating will itself present an impedance and will, therefore, serve to limit the current. Footwear and ground resistivity will also alter the impedance of any current path involving the feet. When applying such criteria, the possibility of coming into contact with an uncoated portion of pipeline (either due to touching a large coating defect or a pipeline valve) usually entails that the pipeline coating resistance can not be considered in any calculation.

The second reason for considering induced voltages relates to the pipeline integrity. Under the influence of a high voltage transmission line a pipeline will have voltages established between the outer coating layer and the metallic core. If this voltage becomes too high, coating damage may take place increasing the risk of subsequent corrosion. This corrosion risk can be due to the development of a continuous flow of ac through the coating defect site or due to the increased requirement placed on the pipeline cathodic protection system. It is recognized that higher ac current flows will result in an increased need for cathodic protection [3]. Typical coatings have electrical strengths varying from 20 kV, for a fusion bonded

Manuscript received March 14, 2007; revised July 14, 2007. Paper no. TPWRD-00126-2007.

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Digital Object Identifier 10.1109/TPWRD.2007.916234

epoxy material, to 85 kV for a three-layer coating [4]. These values will drop when defects are developed on the coating during production and installation.

Finally, if a pipeline rises in voltage with respect to the soil surrounding it, equipment that is connected to the pipeline may be damaged. Of particular importance in this regard are impressed current cathodic protection systems that rectify low-voltage ac to provide pipeline protection. These must be protected against the overvoltages that can be induced on pipelines.

It is, therefore, clearly important to assess the voltages induced onto a pipeline by an overhead transmission line. These studies are routine and can be carried out using specialist software. Much of the difficulty in carrying out such studies will only relate to the gathering of accurate input data, soil resistivity data being particularly time consuming to collect in an accurate manner. However, a factor not commonly assessed during pipeline-transmission line interference studies is the impact of switching and lightning surges on the pipeline. In well maintained transmission line circuits, particularly those in areas of high lightning activity, the propagation of lightning surges down an overhead line will be a reasonably regular event. Switching surges will also pass up and down the overhead line whenever switching is carried out locally on the power system.

The literature on this topic is minimal. In the National Association of Corrosion Engineers (NACE) standard recommended practice [5], lightning is described with regard to direct strikes and its ability to cause phase to earth faults on the overhead line. Switching surges and other transients are simply said to cause "a momentary increase in inductive and capacitive coupling on the affected structures" [5]. No quantification of the relative severity of lightning is performed nor is guidance given on how such quantification could be performed. A paper by Lichtenstein [6] also deals with the hazard posed to pipelines by alternating voltages and lightning on transmission lines but has the same limitations as the NACE document.

Pipeline voltages resulting from the propagation of such transients on the transmission line may have the ability to damage the pipeline coating and/or equipment. Anecdotal evidence exists of impressed current cathodic protection systems being damaged at the same time as switching has been carried out on a parallel overhead line and during lightning storms. It is more difficult to assign lightning as the cause of coating damage as such damage can exist for a number of different reasons. However, should voltages rise to the levels described above in the discussion of coating strength, it is likely that coating damage can be caused by lightning and/or switching.

It is more questionable whether these induced voltages can cause electric shock to a person. IEC 60479-4 deals with the risk of electric shock from lightning but only gives general guidance on the comparison of such shocks to those from voltages of a standard power frequency [7]. Significantly though, it does state: "The interaction of a lightning stroke with the victim's body is quite different from the usual experience with electric shock derived from electrical systems. Even very short single impulses of lightning can cause cardio-pulmonary arrest" [7].

Furthermore, IEC 60479-1 states that "for shock durations below 0.1 s, ventricular fibrillation may occur for current magnitudes above 500 mA and is likely to occur for current magnitudes in the order of several amperes, only if the shock falls within the vulnerable period" [8]. Body impedance typically lies between 500 Ω and 1000 Ω for voltages above 1000 V, assuming that the skin impedance is not significant as for high voltages it is usually broken down [8]. IEC 60479-2 [9], which deals with the effects of short duration currents, states that at this minimum duration (of 100 μs) there is a risk of death associated with a current flow of around 8 A, at the higher end of that discussed by IEC 60479-1 [8]. Assuming a worst case body resistance of 500 Ω, an 8 A current would need to be driven by a 4-kV voltage. This would not cause death in every case as the shock would need to be at the "vulnerable" period of the heartbeat and factors such as coating resistance could decrease the current flow as described for power frequency currents earlier. However, this magnitude of voltage seems appropriate to use as a reasonable estimate of the safety level.

Previous work by the authors used a circuit-based model of a 132-kV transmission line and pipeline to investigate some of these issues [1]. For a 1-km section of parallel pipeline and transmission line, a lightning surge with a peak value equal to the basic impulse level of the transmission line was shown to produce the highest voltage on the pipeline. A switching surge produced significantly lower voltages on the pipeline although these could still be enough to cause problems for pipeline connected equipment. By modeling only a single overhead line conductor on which the transient existed produced no more than a 5% error in comparison to modeling all overhead line phases. However, it did result in significantly reduced computation times.

Soil resistivity was shown to increase the pipeline-induced voltages in approximate proportion to the logarithm of the soil resistivity. Soil resistivity had a slightly higher influence on the induced voltages observed when transients are present on an overhead line in comparison to the case where 50-Hz power frequency current flows.

As the length of parallelism increased from 100 m to 1 km, the level of induced voltage seen on a pipeline due to a transient increased. However, this increase was nonlinear with parallelism length.

This paper further investigates the level of coupling observed on longer pipelines for parallelism lengths up to and including 10 km. It also studies buried pipelines and models a back-flashover events when lightning strikes a tower in proximity to a pipeline.

II. System Modeling

A. Description of Transmission Line and Pipeline

The system modeled consists of a 132-kV overhead line and a parallel pipeline. The 132-kV overhead line is a double circuit three phase line with the lowest conductors placed 20.85 m above the ground. Single ACSR "Hawk" conductors are used for the phases and the shield wire. The phase rotation is as shown on the diagram in Fig. 1.

The pipeline has a 0.6096 m $(24'')$ outer diameter, a wall thickness of 7.9 mm and its steel core has a resistivity of 0.22 $\mu\Omega\mathrm{m}$ and a relative permeability of 100. The pipeline is protected by a 2.5-mm anti-corrosion coating, with 0.1 $\mu\mathrm{S/m}$ conductivity and a relative permittivity of 3. The pipeline is placed

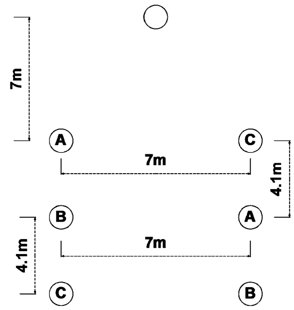

Fig. 1. Phase positioning and dimensions of the 132-kV overhead line.

either 1 m above or 1 m below the ground. In the latter case, it will only be subject to inductive coupling while in the former it will be subject to both capacitive and inductive coupling.

B. Modeling for Cases Involving No Conductive Coupling

Three cases are modeled with no conductive coupling taking place. The first is a reference case with power frequency current flowing along the overhead line conductor to simulate the inductive coupling expected during the passage of both load and fault current. For the aerial pipeline case, the effect of capacitive coupling was also included by elevating the overhead line conductors to the appropriate voltage. This analysis is performed with the assumption that the fault is remote from the pipeline/transmission line parallelism and conductive coupling is therefore neither modeled nor discussed. A further simplification is made whereby the magnetic field reducing effect of return current flowing through the shield wire is not modeled. For the 132-kV transmission line model a typical load current would be in the order of 200 A rms while the phase to earth fault current would be 2-kA rms.

Switching surges are reasonably straightforward to model as they are generated at a location where some form of switching can take place such as a substation or a generation plant. The maximum value of switching impulse that could be expected on a 132-kV overhead line is around 3 p.u. or 325-kV peak (phase to earth). In the simulations, a voltage source injects an impulse of the appropriate shape into the overhead line. The overhead line has a given surge impedance and, in accordance with traveling wave theory, the voltage impulse can be described as being equal to a current magnitude determined by the division of the peak of the injected voltage with the overhead line surge impedance. Capacitive coupling and inductive coupling are therefore both modeled using the single injection of voltage.

The lightning surge that has been modeled has a 650-kV peak (i.e., the basic impulse level of a 132-kV system). In an identical way to the switching surge, a voltage source is used to inject this surge. Capacitive and inductive coupling are therefore both modeled in this case. This case models the passage of a lightning transient down the overhead line without the passage of any current in or out of the soil, i.e., it is effectively a case where the overhead line has been struck remotely.

C. Modeling of Overhead Line Backflashover

If the shield wire of the overhead line is hit by lightning, then below a certain current level, this current will simply propagate in both directions along the shield wire and down any tower in the propagation path. When the current rises above a given level, the voltage of the struck tower will rise enough to flashover the line insulation resulting in a backflashover. This will, therefore, result in the propagation of a lightning transient down the phase conductor to which the flashover has taken place. It will also result in the passage of 50-Hz phase to earth fault current. This case is modeled in this paper and therefore examines inductive, capacitive and conductive coupling. Two simulations had to be carried out, one for the lightning strike and another one to assess the voltage of the pipeline during the flow of 50-Hz fault current.

D. Simulation Techniques

Two simulation techniques are used in this paper, performed with the Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) software package. A circuit-modeling technique is used to perform the analysis when there is no conductive coupling. This technique is an established one for lower frequency studies of transmission line interference [10] and has been shown to be valid for studies with higher frequencies within the constraints of this work [1]. The use of a circuit-based technique is preferable to the use of a field-based technique in terms of the time taken per simulation. A field-based approach, which must be used for the backflashover simulation as conductive coupling can be accurately accounted for, takes around 24 h to simulate the response of the pipeline to a single surge compared to around 30 min for a circuit model with a 1-km parallelism.

In the circuit model, the self and mutual impedances of all the conductors within the system are computed and used to determine voltage and current distributions for a specific frequency. The field-based model also determines voltage and current distributions but performs calculations based on Maxwell's equations. In both cases, the response of the pipeline to a transmission line transient in the time domain is generated using results from the simulations carried out at multiple values of frequency and Fourier transforms.

In accordance with the flowchart shown in Fig. 2, a transient surge (either switching or lightning) is transformed into its frequency components by a forward fast Fourier transform (FFT) operation. A double exponential waveform of the form given as (1) is used to simulate the lightning/switching surge and this has the resulting frequency spectrum detailed in (2). A finite number of frequencies constituting a representative sample of the frequency spectrum of the surge are selected and the voltage induced on the pipeline is then evaluated for each frequency (noting that a different simulation software is used at this point depending on whether the simulation is concerned with conductive coupling or not)

$$f(t) = A\left[e^{-at} - e^{-bt}\right] \tag{1}$$

$$F(\omega) = A\left[\frac{1}{a+j\omega} - \frac{1}{b+j\omega}\right]. \tag{2}$$

This leads to the production of a frequency spectrum giving the response of the pipeline to a 1 p.u. (i.e., 1 V) energization on the overhead line. The frequency spectrum inevitably contains resonances at various frequencies and the software automatically detects such areas in the frequency spectrum where the pipeline

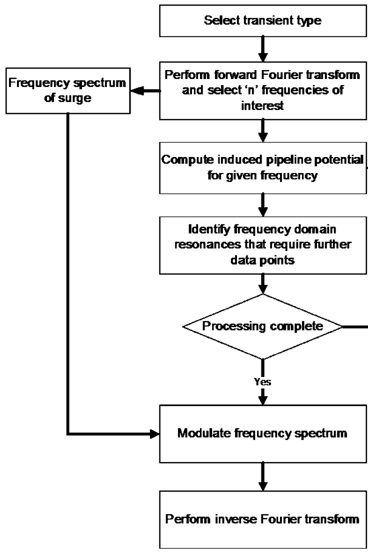

Fig. 2. Flowchart for obtaining time-domain response of pipeline to an overhead line transient.

TABLE I
SURGE IMPEDANCE AND TRAVELING WAVE VELOCITY OF PIPELINE AND OVERHEAD LINE

	Surge Impedance - Ω	Traveling Wave Velocity - m/μs
Pipeline (Aerial)	155	250
Pipeline (Buried)	7	12
Overhead Line	520	300

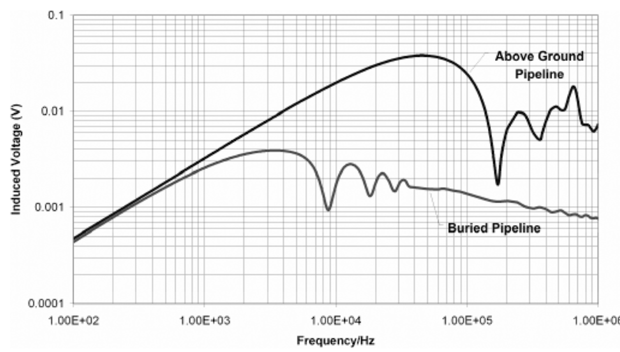

Fig. 3. Maximum voltage observed on an above-ground and buried pipeline for a 1-V injection onto the overhead line plotted against frequency.

response is not fully detailed. Further computations at additional frequencies are carried out until the frequency spectrum is accurately described by a number of discrete simulation results. By using the forward FFT of the originally selected surge to modulate the computed frequency spectrum, the pipeline time domain response can be found using an inverse FFT.

The response of the pipeline to a 1 p.u. overhead line energization has to be calculated only once for a specific geometry and/or soil resistivity. The same frequency response can then be modulated with the frequency content of either a switching or a lightning surge saving valuable computation time when the response to different surge types is required. Further details about circuit and field-based simulation techniques can be found in papers by Dawalibi *et al.* [10], [11].

III. RESULTS OF CIRCUIT-BASED SIMULATIONS

A. Calculation of Transmission Line and Pipeline Surge Impedance

In the simulations carried out to determine the magnitude of induced voltages from transients, surge impedance terminations are used on the overhead line and the pipeline. To determine the transmission line and pipeline surge impedances and thus stipulate the value of these within the final model, simulations were carried out with a single conductor (overhead line or pipeline) beings modeled. Surge of 1 V was injected into one end of the conductor with the other end being left open circuited. The resulting current waveform at the surge injection point can be used to determine the surge impedance and the traveling wave velocity (by examination of the reflections from the open-circuit point). These corresponding values for the three types of simulated conductors are presented in Table I.

B. Frequency Response of Pipeline to a Voltage Injected Into the Overhead Line

When a pipeline is subject to inductive and capacitive coupling, the maximum voltages will be observed at the ends of the pipeline if it is not directly grounded at any point. Fig. 3 shows the frequency spectrum of the voltage observed at the start of an above ground and a buried pipeline placed directly underneath a single phase conductor (the soil resistivity in the following simulations being set to 100 $\Omega\mathrm{m}$). The figure was produced using the circuit-based technique, the results of which have been compared with a field-based technique in a previous paper [1] and shown to be accurate.

The phase conductor is placed in the same location as the lowest phase C in Fig. 1 and 1 V is injected into the overhead line at one end, the other end being terminated with the overhead line surge impedance. The pipeline is terminated at both ends by its surge impedance (use of surge impedance terminations is preferred for this modeling for ease of interpretation of results). The induced voltage rises from 0 V at 0 Hz (not on the graph) to a clearly observable resonance. For the buried pipeline, the resonance is at around 3.5 kHz while for the above-ground pipeline it is at around 40 kHz. The low resonant frequency of the buried pipeline is associated with the high capacitance to earth created by the pipeline coating.

It is more important to consider the frequency spectra when it has been modulated with the frequency spectra of either a lightning surge or a switching surge. Fig. 4 shows the modulating spectrums of the lightning and switching surges used in the models.

The results of modulating the curves in Fig. 3 with the frequency spectrum of a lightning surge are shown in Fig. 5. Performing an inverse Fourier transform on this frequency spectrum would give the response of the pipeline to a lightning surge in the time domain. Of particular significance is the fact that the resonant frequency of the buried pipeline has dropped to around 2 kHz while that of the above-ground pipeline has fallen to around 5 kHz. This form of plot will be used in the discussion of results examining the dependence of induced voltages on pipeline length and soil resistivity.

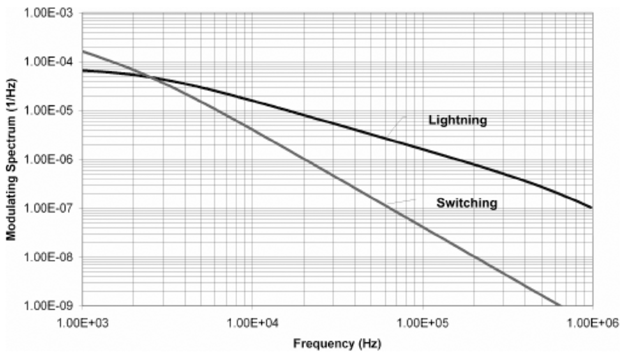

Fig. 4. Frequency spectrum of lightning surge and switching surge.

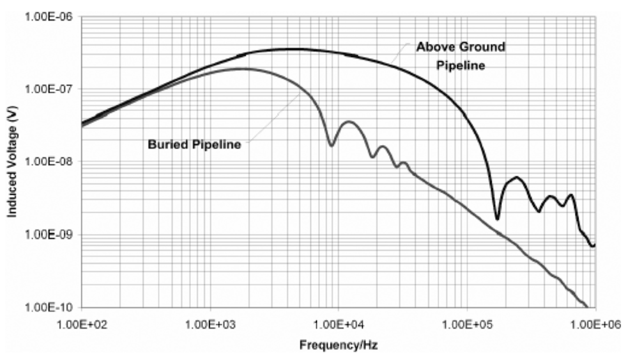

Fig. 5. Modulated spectrum of voltage on an above-ground and buried pipeline for a 1-V lightning surge injection onto the overhead line.

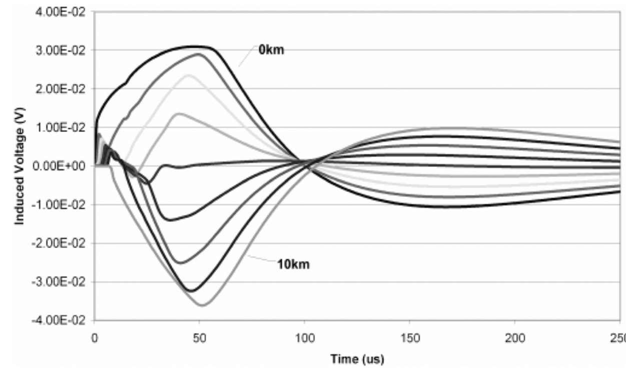

Fig. 6. Time-domain voltages observed on an above-ground pipeline running parallel to an overhead line for 10 km when a 1-V lightning surge is injected into the overhead line.

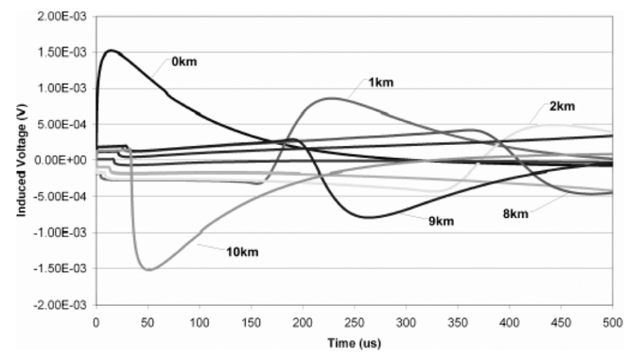

Fig. 7. Time-domain voltages observed on a buried pipeline running parallel to an overhead line for 10 km when a lightning surge is injected into the overhead line.

C. Comparing Induced Voltages on a Pipeline Directly Underneath a Single Phase Conductor in the Time Domain

Fig. 6 shows the voltage induced on an above-ground pipeline where the parallelism length is 10 km. Plots of the voltage are given for the points 0, 1, 2, 3, 5, 7, 8, 9, and 10 km along the pipeline (presented in this order starting from 0 km on the top). The first thing observed is that the voltages are essentially showing the typical profile of being inductively coupled (i.e., positive at one end of the pipeline and negative at the other). There is a slight elevation in voltage at the pipeline end, probably due to a small mismatch in the surge impedance termination. The voltage surges induced at 0 and 10 km travel towards the center of the pipeline, the time taken for 1 km of travel being determined by the traveling wave velocity of the pipeline.

A similar plot is shown as Fig. 7 for the voltages observed on the buried pipeline. An inductive relationship is again observed where the voltages at the far end of the pipeline are negative in comparison to the voltages at the start of the pipeline. However, in this case the voltage at the 10-km end of the pipeline appears some 35 μs after the surge appears at 0 km. This is the time for the lightning surge to travel the full length of the 10-km overhead line. The time of arrival difference between voltages at the other locations of the pipeline (e.g., between 0 km and 1 km) is once again determined by the traveling wave velocity of the pipeline. The voltage waveforms are of a much lower frequency and of a lower magnitude than those observed on the above-ground pipeline.

The small surges which appear at the beginning of Fig. 6 are only present due to the use of the lumped circuit modeling analysis technique. These peaks disappear when similar simulations for 1-km and 2-km pipelines were performed using the field approach on a numerical solution of Maxwell's equations [1]. However, a model of 10 km would have been practically impossible to compute (a single simulation needs more than a month to be completed).

D. Impact of Pipeline Length and Soil Resistivity on the Level of Induced Voltage

The impact of the pipeline/transmission line parallelism length and soil resistivity on both aerial and buried pipelines for switching and lightning impulses is now discussed. Fig. 8 shows the modulated response at the start of a pipeline whose length varies between 100 m and 10 km when a 1-V signal of varying frequency is injected into the overhead line. Results for lengths of 100 m, 200 m, 500 m, 1 km, 2 km, 5 km, and 10 km are given. The results show that as the length of parallelism increases, the resonant frequency of the system decreases. The magnitude of the induced voltage is proportional to length in the low frequency region of the plot but this relationship does not hold true at the higher frequencies.

When these results are transformed into the time domain, the impact of the pipeline's length can be seen on the time domain voltages. Fig. 9 shows the results graphically. The voltage induced on a 100 m pipe is just under 0.02 V for a 1-V lightning surge and is a fast pulse. The longer the pipe, the wider the pulse due to the lower frequency resonance. The figure also shows that the peak magnitude of the induced voltage does not keep

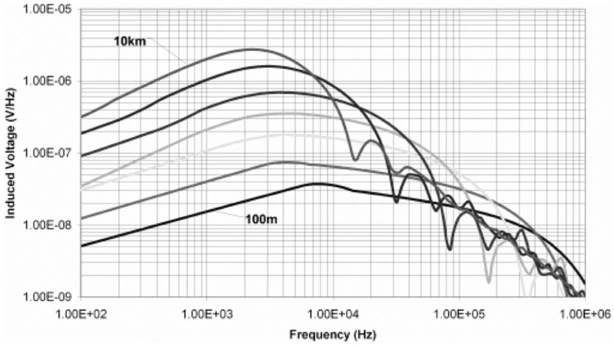

Fig. 8. Modulated spectrum of voltage on an above-ground pipeline for a 1-V lightning surge injection onto the overhead line for parallelisms of between 100 m and 10 km.

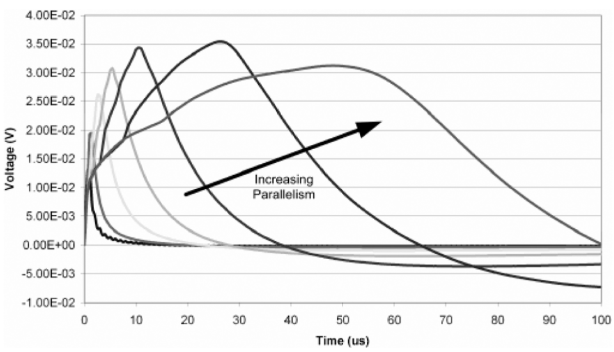

Fig. 9. Time-domain voltages at the start of an above-ground pipeline running parallel to a transmission line for parallelisms between 100 m and 10 km when a lightning surge is injected into the overhead line.

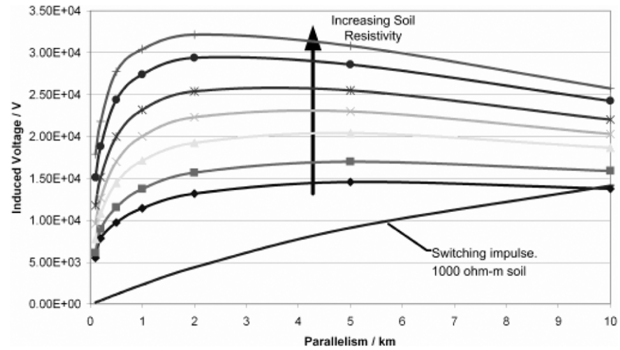

Fig. 10. Peak voltages observed on an above-ground pipeline for different soil resistivities and parallelisms.

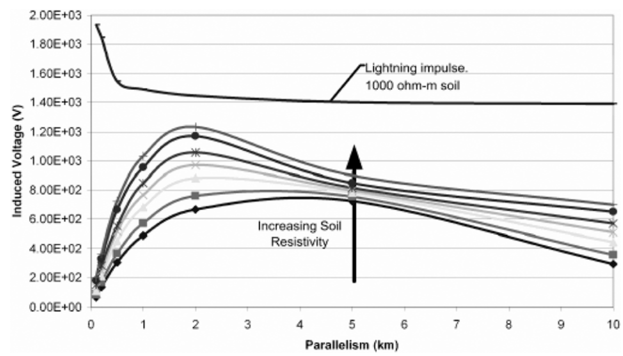

Fig. 11. Peak voltages observed on a buried pipeline for different soil resistivities and parallelisms.

increasing as the parallelism increases. There is a critical distance beyond which the induced voltage begins to fall.

Fig. 10 summarizes a range of results for different soil resistivities. In these studies, the peak voltage on the pipeline is plotted against distance. The results are no longer based on a 1-V injection into the overhead line but are based on the actual values of surge voltage previously presented. Seven curves are given that describe the response of a pipeline to a lightning impulse on an overhead line. The soil resistivities used in these simulations were 10, 20, 50, 100, 200, 500, and 1000 $\Omega\mathrm{m}$. In all cases there is a critical parallelism length above which the peak-induced voltage begins to fall; the higher the soil resistivity, the shorter this distance. The reason for this effect is attributed to the shift in the resonant frequency of the system to a continually lower value as the pipeline length increases.

Also plotted on Fig. 10 is a single curve showing the response of the pipeline to a switching surge on the overhead line. The magnitude of the induced voltage is lower than the corresponding values for a lightning surge. In this case the induced voltage continues to increase as a function of parallelism. However, it is assumed that this would also reach a peak at some critical distance.

Fig. 11 shows the peak voltages observed on a buried pipeline as a function of parallelism length. For the buried pipeline, the largest induced voltage was observed on a 100 m parallelism for the case involving a lightning overvoltage. It is assumed that shorter parallelisms would lead to higher levels of induced voltage although this is not a practically interesting case. The figure also presents the results of injecting a switching surge for a range of soil resistivities. Again, a critical distance is observed that is lower as a function of soil resistivity.

The application of these results in the context of a real power system is discussed in Section V of this paper.

IV. Results of Field-Based Simulations

The simulations just described concern the passage of a lightning transient or of a switching surge down the phase conductors. For switching surges, no current should usually enter the earth and, therefore, conductive coupling should never result. For lightning surges, this would not be the case should lightning hit the transmission line tower or a shield wire. In this case, lightning current will flow directly into the earth. A back-flashover taking place following this flow of lightning current would also result in 50-Hz current being conducted into the earth. Simulations regarding the voltages seen on a pipeline following a tower strike and the resulting flow of follow current have therefore been carried out.

A 132-kV double circuit transmission suspension lattice tower (D-SH L3 STD) was modeled according to U.K. standards and placed 50 m from the underground pipeline. The tower's grounding system was modeled simply using four 2.5-m-long vertical rods. These are each connected to one of the four tower legs and have a 50 Ω resistance, giving an overall grounding resistance of 12.5 Ω. The underground pipeline and the shield wire are modeled with matching impedance terminations. Fig. 12 illustrates the model built in CDEGS as

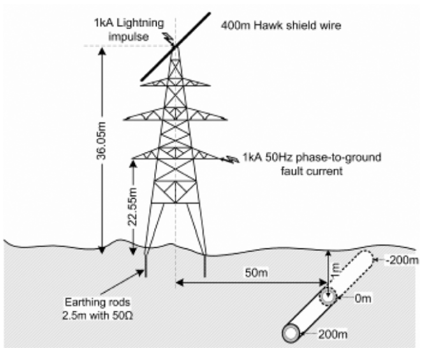

Fig. 12. Schematic representation of the physical structure used to identify the impact of conductive coupling on the coating stress voltage.

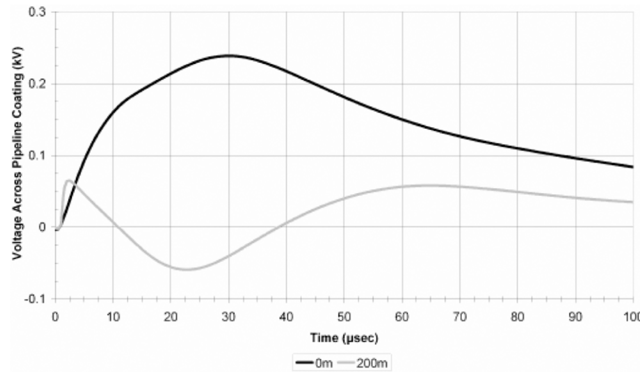

Fig. 13. Stress voltage (in time domain) across the pipeline insulation developed at 0 m and 200 m points during the 1-kA lightning impulse.

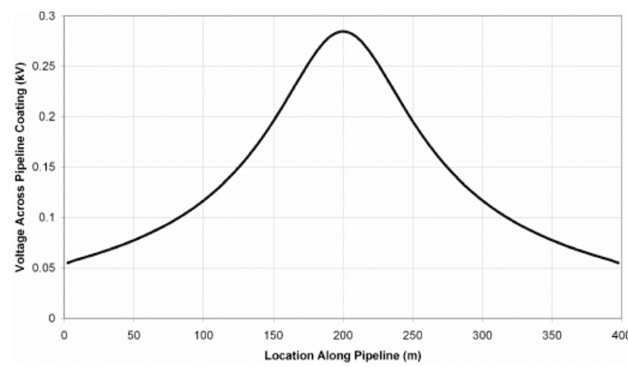

Fig. 14. Stress voltage across the insulation developed along the pipeline length during the 1-kA phase-to-ground 50-Hz fault current.

well as the points where the 1-kA lightning impulse and the $50\ \text{Hz} - 1\ \text{kA}$ current source were applied (two simulations were used to represent the flow of lightning current and the flow of 50-Hz current).

In these simulations, a number of mechanisms give rise to voltages in the soil and on the pipeline. For the 50-Hz case, no inductive coupling should occur as the current has not been made to flow along any phase conductor. In this case, the earthing system will raise the potential of the soil and this will impose a voltage on the pipeline coating. A proportion of this will be conducted onto the pipeline depending on the earthing configuration of the pipeline. If the pipeline is perfectly earthed at both ends, little voltage would be expected on the pipe given the short length. If the pipeline is earthed through an impedance, a higher voltage will appear on the pipe reducing the potential difference seen across the pipeline coating. The main danger in this case would be damage to the integrity of the pipeline or, electric shock for anyone in contact with a pipeline valve or something similar.

Regarding the study which involves lightning, conductive coupling will again raise the potential of the soil and this will stress the pipeline coating. However, as lightning current flows down the shield wires, a voltage will also be induced onto the pipeline through inductive coupling. As the propagation velocity of the surge in the tower/soil will be different to that in the pipe, this will lead to a more complex relationship between the voltages on the pipeline coating and the pipeline itself.

The voltages across the pipeline coating at its center and at one end are shown in Fig. 13 for the case of lightning current flowing down the tower. A positive voltage infers that the coating potential is higher than that of the pipeline. At the center of the pipeline, inductive coupling from lightning current flowing along the shield-wire would not be expected to raise the potential at the midpoint (as shown by previous results). The voltage seen across the coating at this location is, therefore, only produced by the elevation of the soil potential and the resistivity of the coating. The voltage reaches a peak of 239 V for an injection of 1 kA.

For the pipeline end, a more complex shape of voltage is seen. This voltage is a combination of the conductively coupled voltage and an inductively coupled one. Instead of mirroring (or at least being a proportion) of the voltage seen at the center of the pipeline, the inductively coupled voltage at this end of the pipeline causes the voltage across the pipeline coating to become negative.

TABLE II
VOLTAGES OBSERVED ON PIPELINE, ON PIPELINE COATING AND ACROSS THE PIPELINE COATING FOR SIMULATIONS INVOLVING CONDUCTIVE COUPLING

	Pipeline Voltage	**Coating Voltage**	**Stress Voltage**
Lightning	1.4kV	1.4kV	239V
50Hz (RMS values)	18V	302V	284V

Fig. 14 illustrates the voltage across the coating developed during the 50-Hz phase-to-ground fault as a function of length. This graph is straightforward, the highest voltage being seen close to the tower. (However, this could not be true when there is a defect in the pipeline coating). The magnitude of voltage seen across the coating is virtually identical to that seen in the lightning simulations.

Table II gives the peak pipeline voltage, the peak coating voltage and the peak voltage across the coating (the stress voltage) for the lightning and the 50-Hz simulations. In all cases, the peak voltage is observed at 0 m.

For the 50-Hz event, the voltage on the pipeline itself is very low due to the 8.5 Ω terminations that remain on the pipe. The bulk of the voltage in the earth is, therefore, dropped across the coating. Should the pipeline be open-circuit at both ends, a significant reduction in pipeline voltage would be expected.

TABLE III
COMPARISON OF ALL SIMULATION RESULTS

	Above Ground	Buried
50Hz Fault	301V+687V/km	0V+687V/km
Lightning Impulse	23.0kV	1.1kV
Switching Impulse	10.5kV	1.0kV
Backflashover	N/A	47.8kV (lightning current) 568V (50Hz current)

For the lightning surge, the peak voltage across the coating is also around 240 V but the peak voltages on both the coating and the pipeline are higher. These high voltages are not due to the conductive coupling itself, which is only responsible for the 240-V voltage across the coating. The peak voltages are, instead driven by inductive coupling between the lightning current on the shield wire and the pipeline.

V. Comparison of Results

To compare all of the results presented, a summary has been produced and is presented in Table III. The first row of the table gives the voltages induced on the pipeline by the flow of 50-Hz fault current along the overhead line to a fault away from the pipeline (i.e., one where conductive coupling can be ignored). A fault current of 2 kA is used in this calculation. Inductive coupling would be proportional to the pipeline length so the results are given per kilometer of parallelism. The effect of capacitive coupling is given in volts, as it is independent of the pipeline length. This result assumes that the pipeline is open circuit at both ends (10 MΩ) and that no fault current is returning through the overhead line shield wire (the worst case for this calculation). This study was carried out for a 100 Ωm soil resistivity. Rms voltages are presented. The use of a pipeline that has both ends resistance grounded will generally yield lower voltage values than those presented so the results are worst case.

The table then gives the maximum voltage observed on the pipeline for a lightning surge or switching surge propagating along a parallel overhead line. The worst case value from the 100 Ωm studies was taken for consistency.

In the case of the buried pipeline with conductive coupling, the lightning results were scaled to a worst-case current of 200 kA [12]. The result presented is the voltage across the pipeline coating. The 50-Hz result is also scaled to a fault current level of 2 kA. Again, rms voltages are presented.

For an above-ground pipeline for which conductive coupling would be an issue, lightning impulses and switching impulses produce significant pipeline voltages. However, once the parallelism length is over some tens of kilometers, voltages induced from 50-Hz faults are likely to give rise to more significant problems (although this depends on the exact level of return current flowing through a shield wire).

For a below ground pipeline, the levels of induced voltage from lightning and switching impulses are much lower while the level of 50-Hz-induced voltage remains the same. In this case, apart from extremely short parallelisms, it would appear that lightning and switching voltages would not be significant. However, careful consideration is clearly needed regarding protection of a pipeline from conductive coupling which has the ability to cause voltages that would certainly damage the pipeline coating and that could be a threat to human life.

VI. Conclusions

This paper has examined the impact of lightning and switching surges on a pipeline placed parallel to a transmission line for different lengths of parallelism and different soil resistivities. It has also examined the impact of conductive coupling between a tower footing and a pipeline.

For both buried and above-ground pipelines, studies for parallelism lengths up to 10 km showed that inductive coupling produces a voltage on a pipeline when a lightning/switching transient flows along an overhead line. The time at which the voltage appears on the pipeline is partly determined by whether the pipeline is above or below ground (as this decides whether capacitive coupling is a factor) and the overhead line/pipeline traveling wave velocities. The lower resonant frequency of a longer pipeline gives rise to induced voltage pulses of longer duration.

A critical length has been identified beyond which extension of the parallelism does not result in an increase in the induced voltage level when a lightning/switching surge passes down an overhead line. The lowest critical length exists for a fast surge being coupled into a buried pipeline. The critical length is also dependent on soil resistivity.

When a backflashover event occurs on a transmission line, a complex voltage waveform will appear across a pipeline coating due to conductively and inductively coupled voltages being of different shapes and appearing at different durations.

It is clear from the results that for an above-ground pipeline, induced voltages from lightning and/or switching events are significant in comparison to 50-Hz faults. This would be the case for parallelisms up to some tens of kilometers. A buried pipeline is, however, protected from the effects of lightning/switching surges due to its low resonant frequency and in this case, 50-Hz events are a major factor to consider in design. Protection of a buried pipeline from conductive coupling has also been shown essential given the levels of voltage that could be developed across the pipeline coating during the passage of lightning current.

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