Comparison of Transient and Power Frequency-Induced Voltages on a Pipeline Parallel to an Overhead Transmission Line

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***Abstract*—An analysis of the voltages induced on a 1-km pipeline by a parallel overhead transmission line has been carried out when the transmission line is carrying power frequency (50 Hz) current and when it is subject to the propagation of a lightning or switching transient. A frequency-based circuit modeling technique coupled with forward and inverse Fourier transforms is used to carry out this analysis. The relative severity of the induced voltages from power frequency current or transient (lightning/switching) overvoltages is illustrated using the simulation results. The results demonstrate the high relative magnitude of induced pipeline voltages that result from the propagation of lightning transients down overhead lines. The need to model the full overhead line for such an analysis is investigated as is the variation of the level of transmission line/pipeline coupling as a function of the local soil resistivity. Analysis of the level of induced voltage as a function of length of parallelism is also carried out.**

***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 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 both a capacitance to the transmission line and to earth. They therefore effectively act as a potential divider. 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 earth. For example, if a phase-to-earth 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 will take 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 from 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 V and 1500 V [1].

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 ensures that the pipeline coating resistance cannot be considered in any calculation.

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The second reason for being concerned in regards to induced voltages relates to the pipeline integrity. A pipeline under the influence of a high-voltage transmission line will have voltages established between the outer coating layer and the metallic pipeline. If this voltage becomes too high, coating damage may take place, giving rise to the risk of subsequent corrosion. This corrosion risk can be due to the development of a continuous flow of alternating current (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 [2]. Typical coatings have electrical strengths varying from 20 kV for a fusion bonded epoxy material to 85 kV for a three-layer coating [33]. These voltages will not usually be seen across the coatings. However, the electrical strengths given are for perfect coatings, defects in the coating will significantly reduce the dielectric strength figure quoted.

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.

There is minimal literature on this topic. In the NACE standard recommended practice “Mitigation of Alternating Current And Lightning Effects On Metallic Structures And Corrosion Control Systems,” lightning is described in regards 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” [4]. 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 [5] also deals with the hazards posed by alternating voltages and lightning on transmission lines to pipelines but has the same limitations as the NACE document.

Given the current gaps in the understanding of the effect of fast transmission-line transients on pipelines, this paper intends to establish whether such transients are likely to expose the pipeline to a significant risk of damage in comparison to that resulting from power frequency faults. To carry out this task, a pipeline–transmission-line parallelism is modeled over a 1-km distance. This work is carried out to examine the likelihood of lightning or switching surges damaging the pipeline coating/equipment or causing risk to human life.

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 during lightning storms. One utility in the U.K. has also reported anecdotal evidence of impressed current cathodic protection systems failing at the same time as switching has been carried out on a parallel overhead line. 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.

Their ability to cause electric shock to a person is more questionable. 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 [6]. Significantly though, IEC 60479–4 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.”

Further information is found in other members of the IEC 60479 family. 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” [7]. It also states that body impedance typically lies between 500 Ω and 1000 Ω for voltages above 1000 V. This assumes that the skin impedance is not significant as for high voltages that it has usually broken down.

IEC 60479-2 deals with the effects of short duration currents (a minimum duration of 100 μs) [8]. At this minimum duration, it states that 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.

Assuming a worst-case body resistance of 500 Ω, 8-A current would need to be driven by 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.

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 earth. Single ACSR “Hawk” conductors are used for the phases and the shield wire. The phase rotation is as shown in the diagram of Fig. 1.

The pipeline has a 0.6096-m $(24'')$ outer diameter and a wall thickness of 7.9 mm. It is a steel pipeline with the steel having a resistivity of 0.22 $\mu\Omega\mathrm{m}$ and a relative permeability of 100. A 2.5-mm anticorrosion coating is placed on the outside of the pipeline. The coating has a conductivity of 200 $\mu\mathrm{S/m}$ and a relative permittivity of 3. The pipeline is placed 1 m above the ground to ensure it is subject to both inductive and capacitive coupling.

Three distinct situations have been modeled. The first is a reference case where power frequency current flows along the overhead line conductor to simulate the inductive coupling expected during the passage of both load and fault current. This analysis is performed without the use of a voltage source on the line as capacitive coupling is not considered significant in most cases, especially when load/fault currents are flowing on the system. This simulation 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 where the magnetic field reducing effect of return current flowing through the shield wire is not modeled. For the 132-kV transmission line modeled, a typical load current would be in the order of 200 A root mean square (rms) while the phase-to-earth fault current would be 2 kA rms.

Switching surges are reasonably straightforward to model as they will be generated at a location where some form of switching can take place, such as a substation or a generation plant. The rated switching impulse level of 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.

For lightning surges, there are a number of types of study that could be performed. Lightning can hit the phase conductors of an overhead line (an event known as shielding failure) and, depending on the magnitude of the overhead line voltage rise, flashover the overhead line insulation to the tower. The shield wire of the overhead line can also be hit, and 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 a nearby/struck tower will rise enough to flashover the line insulation resulting in a so-called backflashover. This will therefore result in the propagation of a lightning transient down the conductor to which the flashover has taken place. It will also result in the passage of 50-Hz phase-to-earth fault current.

For all of these cases, surges propagate down shield wires/phase conductors. These surges can propagate considerable distances. An overhead line may therefore be hit by lightning away from any parallelism but the surge can then propagate toward an area where parallelism exists. For the cases where conductive coupling, (the flow of lightning current into the tower grounding system) is involved, the impact of that tower earthing system being raised in potential will be limited to the local area of the pipeline and not to a significant section. Conductive coupling has been taken to be outside the scope of this paper. This is due to the simulation of an above ground pipeline. A hazard to human life and to pipeline equipment due to conductive coupling would only occur if either were in close proximity to a struck tower at the time of the strike.

The lightning surge that has been modeled has 650 kV peak. In an identical way to the switching surge, a voltage source is used to inject this surge, the peak current of which can be found by dividing the peak current with the overhead line surge impedance. Capacitive and inductive coupling are therefore also both modeled in this case.

B. Simulation Techniques

A circuit modeling technique is used to perform the analysis. This technique is established for lower frequency studies [9] of transmission-line interference and has been shown to be valid for studies with higher frequencies within the constraints of this work. 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 takes around 24 h to simulate the response of the pipeline to a single surge against around 30 min for a circuit model. A field-based approach does have an advantage in that it could be used to examine conductive coupling accurately but this is not in the scope of this paper.

In the circuit model, the self and mutual impedances of all the conductors within the system are computed and used to determine voltage/current distributions for a specific frequency. To analyze the response of the pipeline to a transmission-line transient, time-domain computation results are generated using results from the simulations carried out at multiple values of frequency and Fourier transforms. The lumped parameter model ensures that the behavior of traveling waves on both the pipeline and the overhead line are accurately represented.

In accordance with the flowchart shown in Fig. 2, a transient surge (either switching or lightning) is transformed into its frequency components by forward fast Fourier transform (FFT) operation. A double exponential waveform of the form given as 1) is to used to simulate the lightning/switching surge and this will have 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

$$f(t) = A\lfloor e^{-at} - e^{-bt}\rfloor \tag{1}$$

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

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

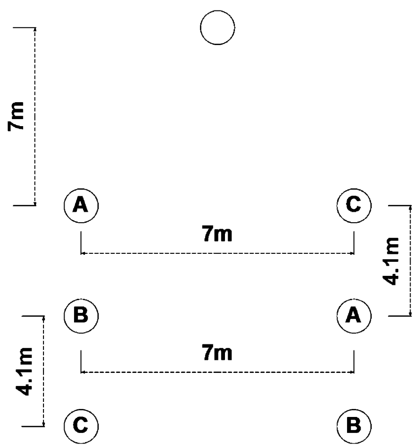

Fig. 1. Phase positioning and dimensions of the 132-kV overhead line. The lowest conductors are 20.85 m from the surface of the ground.

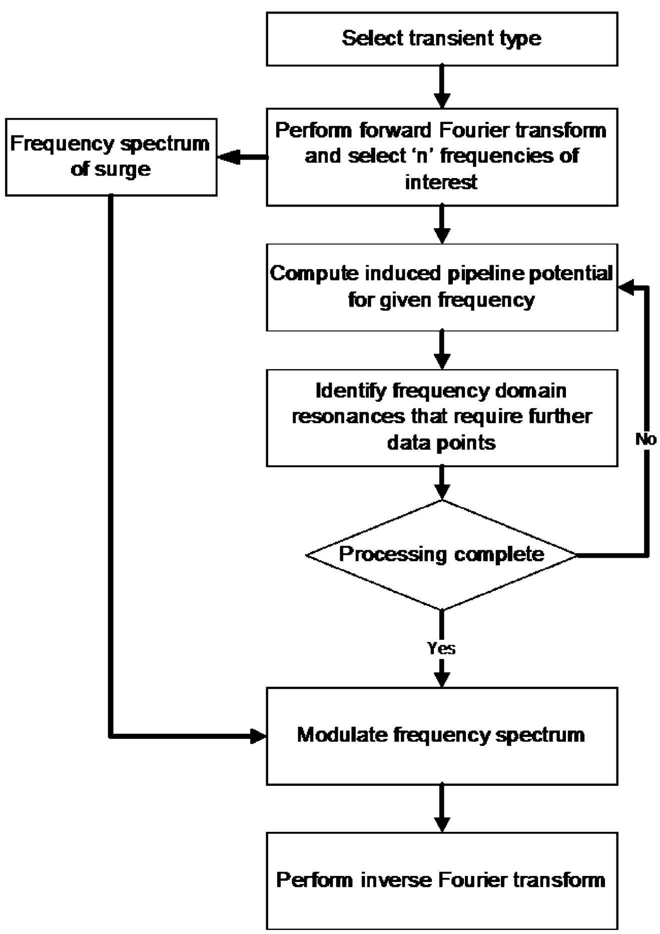

Fig. 2. Flowchart for use in obtaining the time-domain response of pipeline to an overhead line transient.

lected surge to modulate the computed frequency spectrum, the pipeline time-domain response can be found using an inverse FFT.

A significant advantage of this approach is that the response of the pipeline to a 1-p.u. overhead line energization has to be calculated only once for specific geometry/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 of the basis of this technique can be found in a paper by Dawalibi *et al.* [10].

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

	Surge Impedance - Ω	Traveling Wave Velocity - m/μs
Pipeline	142	189
Overhead Line	520	300

III. RESULTS

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 where a single conductor is modeled. A 1-V surge was injected into one end of the conductor with the other end being left open circuit. 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). The results are shown in Table I and describe the surge impedance of the pipeline and the lowest overhead line phase conductor. All other overhead line conductors have similar surge impedances.

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 a pipeline placed directly underneath a single-phase conductor. The frequency spectrum for the far end of the pipeline is identical in shape but is 180° out of phase.

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. The induced voltage rises from 0 V at 0 Hz (not on the graph) to a clearly observable resonance at around 40 kHz. Further smaller resonances can be seen in the frequency spectrum between 100 kHz and 1 MHz. To verify the results of the simulations, a further curve produced by field-based software is shown in this figure. Good agreement is shown with the only differences being related to the exact locations and magnitudes of the high-frequency resonances.

In the next step to produce the response of the pipeline to a lightning or a switching surge, the frequency spectrum shown in Fig. 3. must be modulated using the forward FFT of those surges. Fig. 4 shows the forward FFT results for a 1-V 1.2/50-μs

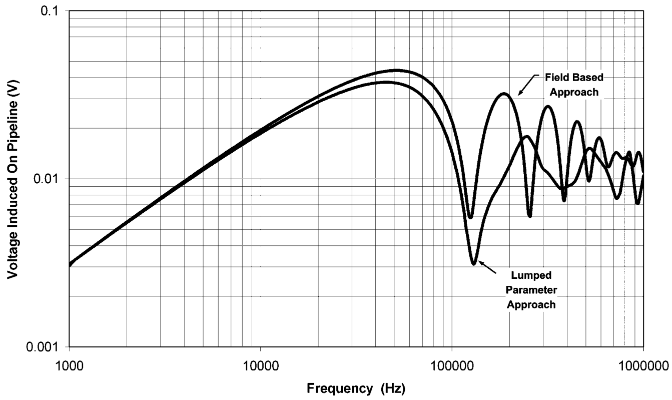

Fig. 3. Maximum voltage observed on pipeline for a 1-V injection onto the overhead line plotted against frequency.

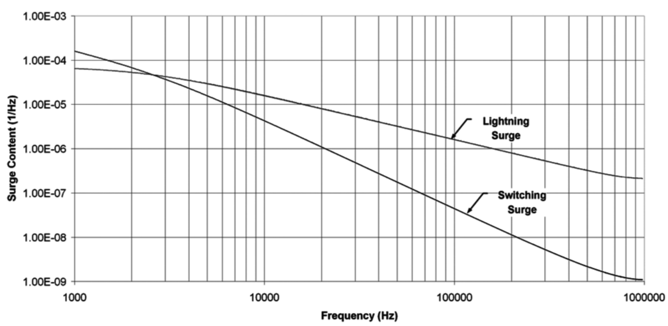

Fig. 4. Frequency spectrum of lightning surge and switching surge.

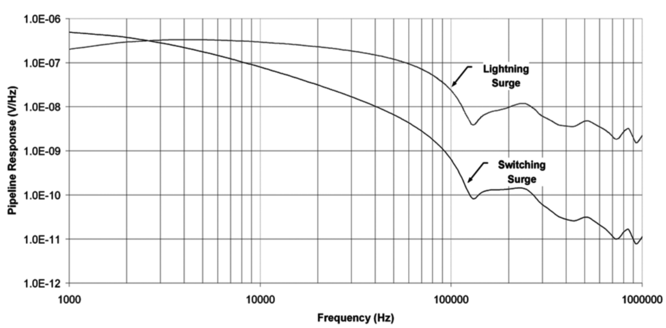

Fig. 5. Modulated spectrum of voltage on a pipeline for a 1-V lightning surge injection onto the overhead line.

lightning surge waveform and a 1-V 250/2500-μs switching surge waveform. The initial number of the xx/yy values refers to the front time of the waveform and the latter number refers to the tail time (the time for the waveform to reach 50% of the peak).

Fig. 5 gives the frequency spectrum of the voltage seen on the pipeline at 0 m for both surge types. This result was produced through the combination of Figs. 3 and 4. The lightning surge is much richer in both intermediate and higher frequency content. The lightning surge can be expected to induce a pipeline voltage with a higher peak value and shorter duration. This will become apparent once the inverse FFT is performed. It is apparent from the figure that the differences between the field-based and circuit-based software at the high-frequency end previously discussed in reference to Fig. 3 will be largely insignificant once the surges have been modulated.

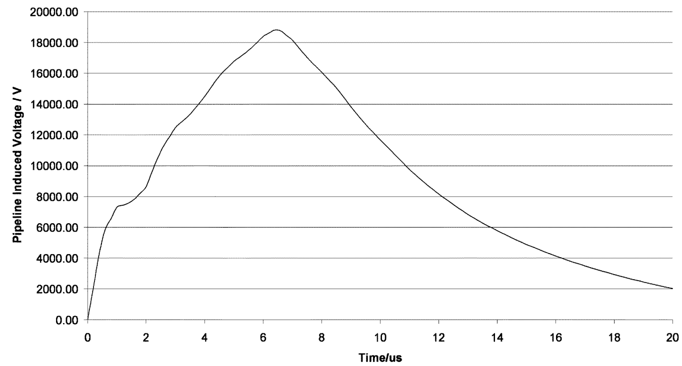

Fig. 6. Time-domain voltage induced at end of the pipeline by a lightning surge.

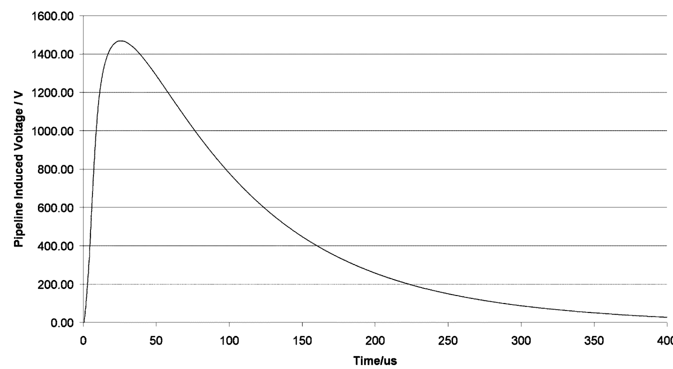

Fig. 7. Time-domain voltage induced at end of the pipeline by a switching surge.

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

By performing an inverse FFT on the modulated spectra given in Fig. 5, the time-domain voltage observed on the pipeline can be calculated. The resulting time-domain waveforms giving the pipeline response to a transmission-line lightning/switching transient are as shown in Figs. 6 and 7, respectively.

The front and tail times of the surge induced on the pipeline by the lightning surge are 6.4 μs and 11.2 μs, respectively. This time differs from the original 1.2-μs and 50-μs values for the lightning surge due to the transfer function acting as a bandpass filter centered at around 40 kHz.

In contrast, for the switching surge, the induced voltage has front and tail times of 27 μs and 106 μs. This compares with values for the actual switching surge of 250 μs and 2500 μs. Conversely to the case for lightning, this is due to an increased contribution of the frequency components in the 40-kHz resonance region.

In addition to these results, a comparison of the pipeline voltage during the flow of 50-Hz current is required. To produce this result, a single frequency-domain simulation is carried out. One ampere of current is injected into one end of the overhead line and is taken to flow freely out of the remote end of the overhead line (therefore not flowing into the ground). As previously described, the simulation does not allow for a reduction in the magnetic field surrounding the overhead line due to current returning through the overhead line shield wire and will therefore give a pessimistic (i.e., excessively high) result for this particular simulation task. For this simulation, the overhead line was also not elevated in voltage as during a fault; it would be usual for the voltage to significantly reduce on the power system. This means that inductive coupling is the only significant interference mechanism in this simulation.

In Table II, a comparison of the results are shown. The maximum voltages that are induced on the pipeline are presented. These are calculated using the values in Table II and scaling them using the typical values for a 132-kV transmission line presented in Section II-A. In the case of the 50-Hz current, the fault current level is used as the scaling factor. Load current will normally result in a very low induced voltage owing to its low magnitude and balanced three-phase nature.

It is clear that a lightning surge gives by far the highest voltage on the pipeline at 18.3 kV. This could realistically cause damage to a pipeline coating or to any impressed current cathodic protection system used by the pipeline. The 50/60-Hz values are significantly lower although they would exist on the pipeline for a longer period of time.

A limitation of these results worthy of note relates to the nonlinear effects of overhead line corona that are not easily modeled in lumped parameter software operating in the frequency domain. When an overhead line is raised in voltage, the increased electric field around the conductor will cause corona to form. This has a resulting effect of increasing the apparent diameter of the conductor and this would raise the mutual capacitance between the overhead line and the pipeline. Energy losses would also take place from the overhead line due to the corona.

D. Modeling of All Overhead Line Phase Conductors

In the initial analysis, only one conductor of the overhead line was modeled. The voltage will clearly be different depending on the location of the lightning surge (i.e., is it on the A, B, or C phase of the overhead line?). By modeling the complete overhead line, the sensitivity of the pipeline voltage to the location of the lightning surge can be ascertained.

The results of this analysis are given in Table III. This provides the maximum voltage observed on the pipeline for a lightning strike to A, B, or C phase of the left-hand circuit. Again, a 625-kV surge was injected (this being equivalent to, and creating on the line, a 1.25-kA current) The pipeline is placed directly under the left-hand circuit for these simulations. The maximum pipeline voltage is presented for the case where only a single conductor (the one carrying the surge) is modeled and the case where all overhead line conductors are modeled. In the latter case, the unused overhead line conductors are taken to be earthed.

The maximum pipeline voltage is the highest when the lightning surge is present on C phase, the lowest of the three conductors. As the lightning surge is moved to a higher phase conductor, the induced voltage is reduced.

When only modeling a single overhead line conductor, it is clear that an underestimation of the peak voltage takes place. Modeling of the entire overhead line increases the peak pipeline voltage by around 4% for A and B phase and by 1% for C phase. This would seem counterintuitive since the lower phases would be expected to shield the pipeline from the electromagnetic fields produced by an energized phase higher up on the tower. However, as can be observed in the frequency spectrum shown in Fig. 8, while the voltage induced on the pipeline is marginally smaller for lower frequencies, there is an increased level of coupling at frequencies in the region of hundreds of kilohertz. This would appear to be responsible for the higher time-domain signal and is confirmed when the time domain plot in Fig. 9 is examined. When the complete line model is used, the voltage is higher but is also marginally quicker to reach a peak indicating the presence of increased high-frequency content.

However, in this particular case, it is clear that when examining coupling of transients between an overhead line and a pipeline, only the phase of the overhead line carrying the transient voltage requires modeling to find the approximate voltage induced on the parallel pipeline.

E. Effect of Soil Resistivity on Induced Voltage

The effect of soil resistivity on coupling between power frequency electromagnetic fields and pipelines is well documented with increased soil resistivity leading to an increase in induced

TABLE II
RESPONSE OF PIPELINE TO POWER FREQUENCY CURRENT, LIGHTNING SURGE AND SWITCHING SURGE PROPAGATING DOWN THE OVERHEAD LINE

Study	Input Source	Coupling Types Modeled	Maximum Pipeline Voltage
50Hz	2kA rms (negligible voltage)	Inductive	264V
Lightning	650kV peak (also equivalent to 1.25kA peak)	Inductive & Capacitive	18,265V
Switching	325kV peak (also equivalent to 625A peak)	Inductive & Capacitive	1,469V

TABLE III
INDUCED PIPELINE VOLTAGE FOR A LIGHTNING SURGE PROPAGATING DOWN A PARTICULAR OVERHEAD LINE PHASE WITH/WITHOUT THE OTHER CONDUCTORS MODELED

Energize d Phase	Voltage For Single Conductor	Voltage With All Conductors	Error When Using Single Conductor
A	14.6kV	15.2kV	-3.95%
B	16.4kV	17.1kV	-4.10%
C	18.3kV	18.5kV	-1.08%

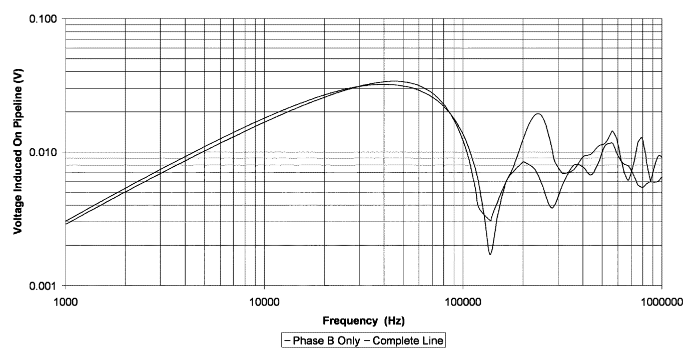

Fig. 8. Maximum voltage observed on pipeline for 1-V injection onto an overhead line (with and without the rest of the line modeled) plotted against frequency.

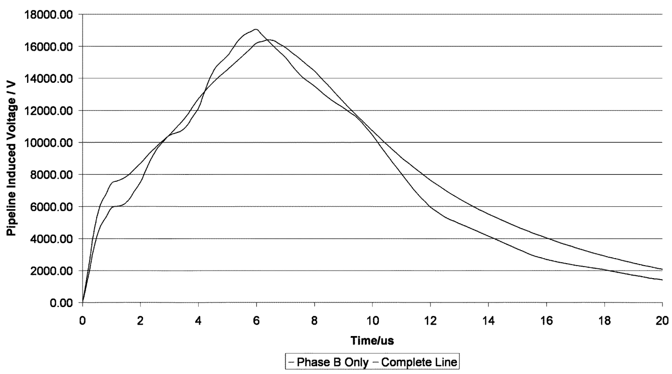

Fig. 9. Time domain voltage induced at end of pipeline by a lightning surge (with and without the rest of the line modeled).

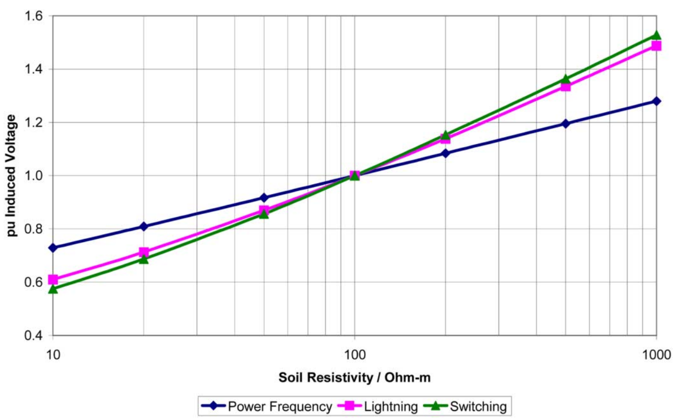

Fig. 10. Variation in pipeline induced voltage according to soil resistivity.

voltage [1]. This relationship is, however, not linear. To confirm whether this relationship holds true for lightning and switching surges, numerous simulations were carried out for the complete overhead line model with different soil resistivity being used in each model. The peak voltage induced onto the pipeline was measured and the value observed for a soil resistivity of 100-Ωm value was chosen as a base to which all of the other results could be normalized.

Fig. 10 shows the variation in the peak-induced voltage on the pipeline for other soil resistivity values between the values of 10 Ωm and 1000 Ωm. In all cases, a relationship of an increase in induced voltage consistent with the log of the soil resistivity is observed. There is a slightly greater dependence of the coupling between transmission line and pipeline for switching and lightning surges. As the power frequency result is a reference, the difference must result from a relative increase in the coupling of high-frequency components, a shift in the resonant frequency at these higher soil resistivity values. Fig. 11 shows the time domain waveforms for a lightning surge inducing a pipeline voltage in 10-Ωm and 1000-Ωm soil.

F. Effect of Parallelism Length on Magnitude of Induced Coupling During a Lightning Surge

For inductive coupling, magnitudes of induced voltages are proportional to the length of parallelism between the transmission line and the pipeline. For capacitive coupling, there is no such relationship, the coupled voltage being constant along the

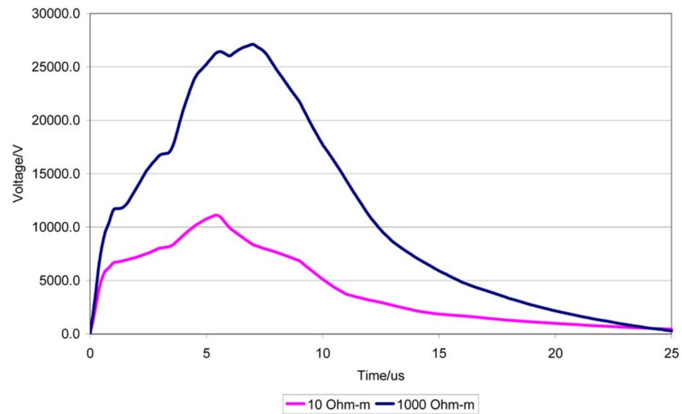

Fig. 11. Variation in time-domain voltage induced on pipeline by lightning transient.

TABLE IV
INDUCED PIPELINE VOLTAGE AND INDUCED VOLTAGE PER METER AS A FUNCTION OF PARALLELISM LENGTH

Parallelism Length / m	Induced Voltage / V	Induced Voltage Per Unit Length / V/m
100	9531	95.3
200	11170	55.8
400	14383	36.0
1000	18265	18.3

pipeline length. Given that lightning surges imposed the highest voltage on a 1-km pipeline, a number of simulations dealing with pipelines of specific lengths were carried out. The full overhead line was again modeled and the voltage at the start of on an above ground pipeline was found in the time domain for pipeline lengths of 100 m, 200 m, 400 m, and 1000 m.

Table IV shows the peak voltages observed on the pipeline as a function of the pipeline length. The voltage induced per meter of pipeline is also calculated and is shown to reduce as the pipeline length increases. This is not typical of inductive coupling between pipelines and transmission lines operating at low frequencies.

An explanation for this result can be found when the induced voltage observed on the pipeline is examined within the frequency domain. In Fig. 12, the induced voltage on a 100-m parallelism and a 1000-m parallelism is plotted. The 100-m results have been multiplied by 10 to normalize them to the 1000-m case. If the level of induced voltage was proportional to the pipeline length, this would lead to overlapping plots.

At the lower end of the frequency spectrum, the expected result is observed. The per-unit length induced voltage on the pipeline does not change. The difference in the results comes from the decreased coupling between the pipeline and transmission line at higher frequencies and a shift in the resonant frequency.

Examining the results suggests that for longer parallelisms, the reduction in coupling at higher frequencies will arise as a result of two factors. The first is the attenuation of a particular frequency of a traveling wave as it moves along the overhead line as this can be expected to act as a low-pass filter due to its series inductance and shunt capacitance. The second reason is attenuation in the pipeline itself which has a higher capacitance

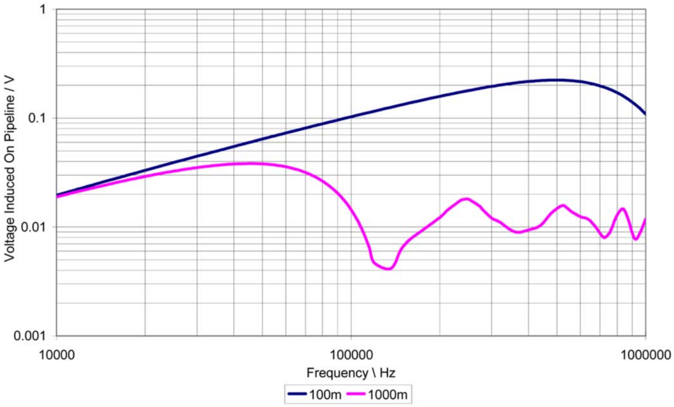

Fig. 12. Frequency domain pipeline induced voltage for a 100-m and 1000-m transmission line—pipeline parallelism (100-m figures multiplied by 10 to normalize plots to per-unit length).

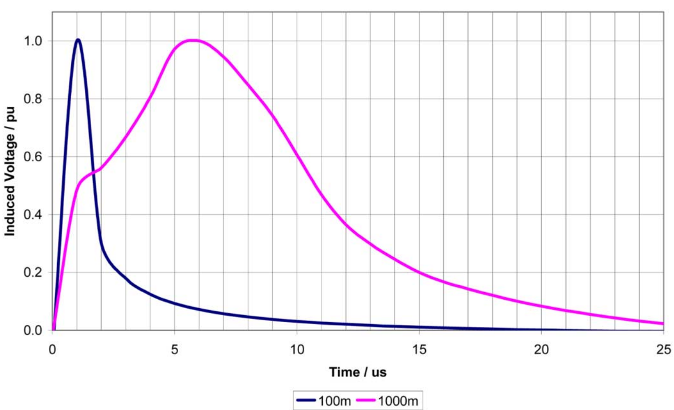

Fig. 13. Per-unit induced time domain voltage for a 100-m and 1000-m transmission line—pipeline parallelism.

to earth than the overhead line and a significant inductance due to the high steel permeability.

Fig. 13 shows the significant effect that the shift in the resonant frequency has on the shape of the induced voltage when a shorter parallelism exists. The time-domain waveform is much richer in high frequencies in comparison to a longer parallelism and the waveform is therefore significantly shorter in duration.

The results indicate that transients voltages are likely to be more significant for pipelines with shorter parallelisms. That is, as for these cases, the transient coupling will be dominant. As the parallelism gets longer, the level of inductive coupling at the low-power system frequencies will continue to increase linearly with distance while the amount of coupling due to transient voltages will rise more slowly.

G. Conclusion

A circuit-based model has been used to investigate the relative importance of 50-Hz fault current, lightning, and switching surges in terms of their likelihood of causing damage to a parallel pipeline or equipment connected to it. A circuit-based approach in comparison to a field-based approach to allow quick simulation times. This was shown to be accurate when compared with the field-based approach.

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 has been shown to produce the highest voltage on the pipeline. The switching surge produces significantly lower voltages on the pipeline although these could still be enough to cause problems for pipeline-connected equipment. Modeling the whole overhead line produces slightly higher predictions of pipeline-induced voltage for the case where a lightning surge is propagating down the overhead line.

Soil resistivity provides an increase in pipeline-induced voltages that is approximately proportional to the log of the soil resistivity. Soil resistivity has 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 increases, the level of induced voltage seen on a pipeline due to a transient is also seen to increase. However, this increase is nonlinear with parallelism length. As the magnitude of low-frequency inductive coupling is linear according to length, transient-induced voltages will be more dominant for smaller lengths of parallelism.

The results clearly demonstrate the significant magnitudes of voltage that can be induced onto a pipeline by a transient voltage, especially a lightning surge. Even for short parallelisms, consideration should be given to the effect of this induced voltage on the integrity of the pipeline coating, any connected cathodic protection system, and human life.

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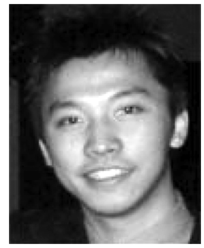

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