The History and Recent Trends of Transient Analysis in Transmission Lines

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***Abstract--* In this paper, the history of a power system transient analysis is summarized starting from “Lord Kelvin arrivel curve” in 1850s to numerical electromagnetic analysis methods which solve Maxwell’s equation directly. Also, the problems of theories and formulas adopted in simulation tools such as the EMTP are explained, and the application limits are discussed**

***Keywords*: transient analysis, power system, EMTP, numerical electromagnetic analysis**

I. INTRODUCTION

A significance of a power system transient and its analysis is not necessary to be explained as the IPST has proved the significance. The first work related to the power system transient, specifically wave propagation on a distributed-parameter line, is so called “Kelvin arrival curve” derived by Lord Kelvin to investigate signal distortion on the planned Trans-Atlantic telephone cable in 1854 [1], [2]. Theoretically the solution was confirmed by Heaviside’s transform which had became the most powerful and promised approach to deal with a transient in an electric circuit until 1960s [3]-[5].

In 1926, a transformer breakdown occurred due to lightning to a 220 kV transmission line in Pennsylvania [6]-[8]. This was an origin of applying a transient analysis to a high-voltage power system. A traveling wave theory, theoretical transient analysis methods etc. were established in 1930s [9], [10]. Also in this time period, accurate formulas of a conductor internal impedance, an earth-return impedance and admittance of an overhead line were derived for studying telephone line interferences from a power line [11]-[15]. In 1960s, a digital computer became available, and an enormous number of engineering researches were carried out all over the world. In 1970, CIGRE WG 13.05 started to investigate various transient simulation methods and carried out a comparison with field test results of switching surges [16], [17], and the WG reached a conclusion that the EMTP was most powerful and useful [18-20].

Recent advancement of ICT technologies, measuring technologies so on has made clear the application limit of a circuit-theory based approach such as the EMTP. Thus, a new approach to deal with such phenomena is required, and a numerical electromagnetic analysis (NEA) is becoming a powerful approach to deal with a transient involving non-TEM mode propagation etc [21]-[24].

This paper first describes the history of a transient analysis in transmission lines from 1850s to the present. Then, the problems and the application limits of a circuit-theory based simulation tool are explained. Finally, a numerical electromagnetic analysis method is described.

II. HISTORY OF TRANSIENT ANALYSIS

A. *Background of transient analysis*

Electrical transients associated with a wave propagation characteristic are mathematically represented by a hyperbolic partial differential equation. The earliest solution of the partial differential equation was given by D’ Alembert for the case of a vibrating string in 1750 [25]. At the same time Bernoulli found a solution which was of quite different form from the D’ Alembert solution. Bernoulli’s solution is based on the eigen function, and is comparable with the Fourier series.

B. *Before 20th century*

The first work related to a power system transient seems Lord Kelvin’s investigation of wave propagation characteristic on the planned Trans-Atlantic telecommunication cable in 1854 [1], [2]. He derived well-known “Kelvin arrival curve”, which expressed a signal distortion along the cable in the form of $\exp(-\alpha x)$ with time delay $\tau = x/v$, v: velocity. The solution is very similar to that of heat-transfer along a heat conducting material.

In the same generation, Heaviside developed so-called “Heaviside transform”, which was the same as Laplace transform, and gave a number of solutions/formulas between time (t) and frequency (ω or $s = j\omega$) functions [3]-[5]. The Heaviside transform was widely used to obtain a transient (dynamic) response in a lumped-parameter circuit, not only for electrical phenomena but also for acoustic, mechanical vibration, heat transfer etc. until 1960s.It is noteworthy to mention that Heaviside derived Maxwell’s equation by applying double integral Heaviside transform [3].

C. *1900 to 1950*

(1): *Lightning surge*

In 1926, the Walenpaupack-Siegfried 220 kV line in northwestern Pennsylvania was put into operation with no

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overhead grounding wire and no arrester at the terminals. A cooperative lightning investigation was begun. Fig. 1 shows field installation of a surge recorder and a voltage divider. In the summer, some of transformers were broken down due to lightning. Next year, the investigation was enlarged and spread to other systems including the Ohio Power Co., the New England Power Co. and the New York Power and Light Co. In 1928, the coordination of transmission line and apparatus insulation was discussed in the AIEE meeting [6-8]. Fig. 2 shows a measured lightning surge waveform.

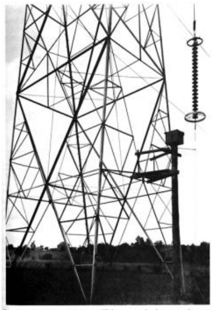
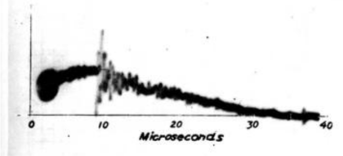
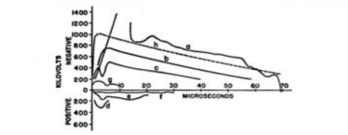


Fig. 1 Installation of a surge recorder and a voltage divider on a 220 kV system [8]



(a) Measured waveform



(b) Reproduced lightning currents

Fig. 2 Measured lightning currents [8]

This was an origin of applying a transient analysis to a high-voltage power system. It was measured that a lightning impulse current was of the waveform with the rise time being around 1 micro-sec. and the tail of about 40 micro-sec as in Fig. 2. At the same time, a traveling wave theory [9], a lumped parameter circuit theory for a transient [10], a basic theory of grounding etc. were established in 1930s and are still widely used. Also in this time period, accurate formulas of a conductor internal impedance [11], an earth-return impedance [12], [13] and an earth-return admittance [14] of an overhead line were derived in Bell Telephone Laboratory for studying telephone line interferences from a power line [15]. Those impedance / admittance formulas are also used still now.

(2): *Switching surges*

When arresters and overhead ground wires became common and the insulation of transmission lines and substation apparatuses were coordinated, a switching surge was focused as a cause of troubles in a power system. To analyze the switching surge and also a fault surge, it is necessary to deal with a three-phase circuit. As a consequence, a symmetrical component theory developed in 1918 [26] was applied to analyze the switching surge [27]-[30].

D. 1950 to 1980

In late 1950s, a digital computer became available, and an enormous number of computer applied researches were carried out all over the world. All the tedious theoretical and hand calculations were replaced with computer simulations. Many computer programs to deal with electrical transients were developed. Among various approaches of solving a transient, a traveling wave technique became one of the most powerful approaches because of the distributed nature of a transmission line. The concepts and the theory of traveling waves have been well developed since D'Alembert's solution. Allievi first applied the theory to the field of hydraulic engineering and established the general theory and the idea of a graphical method which was a direct application of the traveling-wave concept to engineering fields [31]. The method developed by Allievi has been applied to the analysis of a water hammer by Schnyder [32], Bergeron [33] and Angus [34]. This is originally called Schnyder-Bergeron method in the electrical engineering field. The detail and application of the graphical method is well described by Parmakian in his book [35]. The graphical method corresponds to the method of characteristic to solve Maxwell's equation mathematically [36]. The graphical method and Bewley's lattice diagram were implemented on a digital computer for calculating electrical transients [18], [37]-[40]. These techniques are generally called the traveling-wave technique, or a time-domain method.

Numerical Fourier transform appeared in the electrical engineering field only very recently [41]-[44]. Gibbs' phenomena and instability in a transform process, which are the inherent nature of the discrete Fourier transform, are greatly reduced by developing the modified Fourier transform [42], [43]. At a later stage, the modified Fourier / Laplace transform was applied to transient calculations by various authors [45]-[48]. Since the modified Fourier / Laplace transform provides a high accuracy for obtaining a time solution on a frequency-dependent line, and implementation of fast Fourier transform (FFT) procedure into the modified Fourier / Laplace transform greatly improves the computational efficiency [46], the method has become one of the most accurate and efficient computer techniques for transient calculations.

CIGRE WG 13.05 started to investigate various transient simulation methods and carried out a comparison with field test results of switching surges [16], [17]. In 1975, most of the WG members including H. Dommel reached a conclusion that the EMTP developed in Bonneville Power Administration was most powerful and useful [18]-[20]. Thus, many scientists / engineers started to contribute the further development of the EMTP and also to use the EMTP for a power system transient analysis.

E. 1980 to present

Since the EMTP has become a kind of a world standard simulation tool to solve a power system transient, a number of papers have been published. Those are, for example, accuracy improvement and increasing numerical stability which are closely related to the advancement of so-called ICT technology.

III. PARAMETERS REQUIRED FOR TRANSIENT ANALYSIS AND ASSOCIATED PROBLEMS

Any circuit-theory based transient program requires circuit parameters to carry out a simulation. Among the parameters, a series impedance and a shunt admittance are essential for a transient on a distributed-parameter line.

A. *History of impedance and admittance formulas*

The internal impedance of a cylindrical conductor was derived by Schelkunoff in 1934 [11]. The earth-return impedance of an overhead / underground isolated conductor (cable) was developed by Pollaczek [12] in 1926, and Carson derived the same formula as Pollaczek's one but gave an infinite series form for the overhead line case [13]. All the above impedance formulas being given as an infinite integral or as an infinite series including complex Bessel functions, various investigations have been carried out from the viewpoint of numerical accuracy. At the same time, an approximate formula in a closed form was proposed from the engineering practice viewpoint [15], [49]-[52].

In contrast to the impedance, the shunt admittance of a line has not been focused in general. It should be noted that the impedance and the admittance are one pair to express a behavior of a voltage and a current along the line, and thus the accuracy of a simulation is dependent on both the impedance and admittance. Wise derived the shunt admittance for an imperfectly conducting earth [14].

B. *Problems associated with the parameters*

(1): *Earth return impedance*

The reason why Carson's impedance is very popular and widely used is simply due to its asymptotic expression which was only possible way to evaluate the earth-return impedance before a computer. However, the asymptotic expression inherently necessitates formulas for a small variable (low frequency) and for a large variable, and this results in a discontinuity of the calculated impedance as a function of frequency. Also, the accuracy in the boundary region is not high enough. The same is true in Schelkunoff's formula of a conductor internal impedance [11]. Nowadays, the advancement of computer capability makes it possible to calculate Pallaczek's infinite integral.

Pollaczek's and Carson's formulas were derived under the assumption that:

$$\text{length } x \gg \text{height } h \gg \text{radius } r \qquad (1)$$

It should be noted that most formulas of capacitances and inductances of conductors in any textbook are based on the above condition. It is easily confirmed that any capacitance formula gives an erroneously large value when the radius reaches the height. Correspondingly, the inductance of an infinite conductor becomes larger than that of a real finite conductor [53], [54].

Furthermore, the formulas neglect displacement currents, that is :

$$1/\rho_e \gg \omega\varepsilon_e \quad \text{or} \quad f \ll 1/2\pi\varepsilon_e\rho_e \qquad (2)$$

where ρ_e is the earth resistivity, ε_e is the permittivity, and $\omega = 2\pi f$.

For example, the applicable range of a frequency in the case of $\rho_e = 1000\ \Omega m$ and $\varepsilon_e = \varepsilon_0$ is given by :

$$f \ll 18\text{ MHz} \quad \text{or} \quad t \gg 50\text{ ns}$$

Even in the case of $\rho_e = 100\ \Omega\text{m}$, a transient of 10 ns time region can not be simulated by Pollaczek's and Carson's impedance neglecting the displacement currents. Remind that most of frequency-dependent line models are not applicable to the above cases, because the models are based on Pollaczek's and Carson's impedances. Under the condition in which Equations (1) and (2) are not satisfied, only Kikuchi's and Wedepohl's impedance formulas are applicable at present [55]-[57]. This requires a far more advanced numerical integration than that applied to Pollaczek's one.

Pollaczek's and Carson's impedances are for a horizontal conductor. In reality, there are a number of non-horizontal conductors such as vertical and inclined. Although many papers have been published on the impedance of the vertical conductor such as a transmission tower, it is still not clear if the proposed formulas are correct [58]-[61]. Impedance formulas for inclined and non-parallel conductors have been proposed in References [62]. Since the formulas have been derived by the idea of complex penetration depth with Neumann's inductance formula, those require a further theoretical analysis.

Earth is stratified as is well-known, and its resistivity varies significantly at the top layer depending on the weather and climate. The earth-return impedance of an overhead conductor above the stratified earth was derived in Reference [63] and the stratified earth effect was investigated in Reference [64]. The stratified earth effect might be far more significant than accurate evaluation of the homogenous earth-return impedance of Pollaczek and Carson, and this requires a further investigation.

(2): *Internal impedance*

Schelknoff's impedance was derived under the condition that a conductor was in a free space corresponding to Equation (1). Therefore, the impedance is not applicable to a finite-length conductor with a proximity effect. This fact suggests that an internal impedance of the finite length with the proximity effect is to be developed.

Schelkunoff's impedance also assumes that a conductor is circular or cylindrical. In reality, there exist many conductors of which the cross-section is not circular nor cylindrical. Reference [65] derived the internal impedance of a conductor with an arbitrary cross-section, which has been implemented into the EMTP Cable Parameters program [66]. Reference [67] shows an approximation of a conductor with T or hollow rectangular shape by a cylindrical shape conductor. Although the internal impedance of a conductor with an arbitrary cross-section can be accurately evaluated by a finite-element method of numerical calculation, it is quite time and memory consuming. Either an analytical formula or an efficient numerical method needs to be developed.

(3): *Semiconducting layer of cable*

It is well-known that there exists a semiconducting layer on the surface of a cable conductor which occasionally shows a significant effect on a cable transient [68]. The impedance of the semiconducting layer was derived in Reference [69], and may be implemented into a cable impedance calculation. It should be noted that the admittance of the semiconducting layer is far more important than the impedance from the viewpoint of a transient analysis.

(4): *Proximity effect*

Recently it has been pointed out that the proximity effect is significant in a transient state for a surge waveform is noticeably distorted by an increase of a conductor resistance due to the proximity effect [70], [71]. Unfortunately there exists almost no measured data investigating the proximity effect for a transient. Wave propagation characteristics and transients on a pipe-type (PT) cable considering the proximity are easily analyzed by using PT cable option of the EMTP Cable Constants. However, there is no impedance/admittance formula of a multi-conductor overhead line and an underground multi-phase cable.

(5): *Cabtyre cable*

A cabtyre cable, often used in an inverted fed motor system, is composed of a number of covered conductors touched each other. There exists no impedance/admittance formula of the cabtyre cable which involves the proximity between the conductors and multi-layered insulators.

C. *Application limits*

(1): *Assumption and limit of a simulation tool*

It should be noted that most of the existing or well-known formulas of impedances and admittances are derived based on the assumption of an infinity long conductor. The frequency of interests is increasing year by year corresponding to the advancement in measuring equipment: for example 1 GHz sampling frequency of a recent oscilloscope, while some 10 MHz ten years ago. The length is inversely proportional to the frequency, and therefore it becomes necessary to deal with a transient on an 1-m conductor, of which the natural resonant frequency is in the order of 100 MHz. Then, Schelkunoff's, Pollaczek's and Carson's impedances adopted in any circuit-theory based simulation tool may not be applied [23], [24]. The above -explained assumption and the limit should be clearly explained in a rule book of a simulation tool. The best solution which overcomes the above explained problem is physical understanding of the phenomenon to be simulated. That is engineering. We are not computer engineers, nor IT engineers.

(2): *Input data*

Corresponding to the above, a user of a simulation tool should be careful of input data. Quite often the input data beyond the assumption and the limit of the tool are used, and the user complains that the tool gives erroneous output. This is the author's experience as a developer of the original EMTP since 1976. At the same time, both a user and a developer should recognize that there are a number of uncertain physical parameters, typically the earth resistively which varies along a transmission line and also along the depth of the earth. The stratified earth effect on a transient may be far more influential than the accuracy of numerical calculations of the impedance assuming a homogenous earth. It is interesting to state the fact that the stratified earth option of the EMTP Cable Constants has never been used since the year of 1978. Also, stray capacitances and residual inductances of a power apparatus are, in general, not available from a manufacturer. The same is applied to a nonlinear characteristic of the apparatus, and the resistivity and the frequency-dependent permittivity of a cable insulator and the semiconducting layer.

IV. NUMERICAL ELECTROMAGNETIC ANALYSIS

A. *Summary*

The numerical electromagnetic analysis (NEA) method [21]-[24] is becoming one of the most promising approaches to solve transient phenomena which are very hard to solve by existing circuit-theory-based simulation tools. For example, the circuit-theory based approach has the difficulty to solve a transient in a complex media, such as a transient on a grounding electrode and that on a semi-conducting layer of a cable. Furthermore, the circuit-theory approach cannot be applied if circuit parameters are not known. NEA can solve such problems, because the NEA calculates Maxwell's equation directly only with the geometrical and physical parameters of a given system.

A working group of the IEE Japan was founded in April 2004 to carry out an investigation of NEA and application examples. The result of the working group was published as a book from the IEE Japan [22]. Also, CIGRE WG C4. 501 to investigate the NEA was established in 2009 [24], and has completed a technical brochure (TB) which will be published soon.

The NEA method is powerful to deal with a power system transient, for example in the following subjects.

- three-dimensional electromagnetic field analysis
- surge characteristics of overhead transmission-line towers
- surge characteristics of vertical grounding electrodes and horizontally-placed square-shape grounding electrodes
- surge characteristics of air-insulated substations
- lightning-induced surges on overhead distribution lines
- surge characteristics of a wind-turbine tower struck by lightning and its inside transient magnetic field
- very fast transients (VFTs) in gas insulated switchgears

However, as large computation resources are, in general, required, NEA methods can be considered useful tools to set reference cases and study specific problems. Also, a perfect conductor assumption in an FDTD method, for example, results in a difficulty to analyze TEM, TM and TE transition of wave propagation along a lossy conductor above a lossy earth [55], [56], [72].

B. *Various method of the NEA*

Table 1 categorizes various methods of numerical electromagnetic analysis (NEA). The method of moments (MoM) in the frequency and time domains and the finite-difference time-domain (FDTD) method have frequently been used in calculating surges on power systems. Applications of the finite element method (FEM) and the transmission matrix method (TLM) to surge calculations have been rare at present. The MoM and the FDTD method are, therefore, two representative approaches in surge calculations.

A. *Application examples of the NEA*

(1): *Transient responses of a grounding electrode*

Fig. 3 shows a comparison of EMTP and FDTD simulation results with a measured result [22]. The simulation result in Fig. 3 shows a reasonable agreement with the measured result. It should be noted that the EMTP simulation result is quite dependent on the parameters adopted in the simulation which is a function of geometrical and physical constants of a conductor. On the contrary, an FDTD simulation depends very

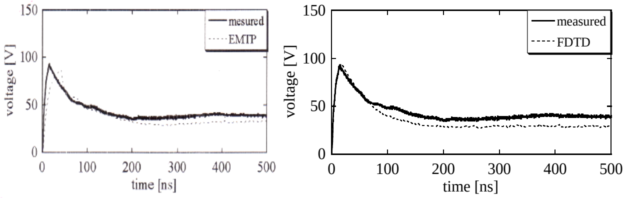
Table I Various methods of numerical electromagnetic analysis

partition	space					boundary
discretization/ domain	finite difference		boundary length		finite element	
time-domain	FDTD	TD-FI	3D circuit	TLM	TD-FEM	MOM (TWTDA)
frequency	—	FI	—	—	FEM	MOM
base equation	Maxwell differential	Maxwell integral	Maxwell characteristic	D'Alembert solution		field integral
feature	easy programming	multi media	circuit theory extension		wide application	Small CPU nonlinear in time domain

much on the analytical space, absorbing boundary, cell size and time step. The above observation has indicated that the EMTP has been numerically completed quite well, while the FDTD requires a further improvement of its numerical stability.

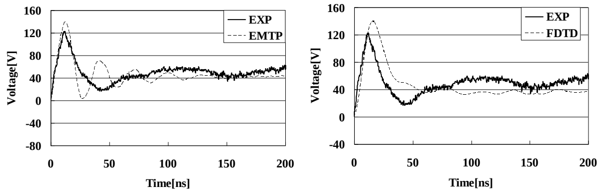
(2): *Transient response of a tower*

Fig. 4 shows measured result of transients in a chemical plant, and corresponding simulation results by the EMTP and FDTD simulation results [22]. It is observed that the simulation results agree reasonably well with the measured result. A difference observed between the measured and the EMTP simulation result is estimated due to mutual coupling between the tower, the pipeline and measuring wires. A difference between the measured and the FDTD simulation results seem to be caused by a perfect conductor assumption of the FDTD method.



(a) EMTP (b) FDTD

Fig. 3 Measured and simulation results of a grounding electrode voltage



(a) EMTP (b) FDTD

Fig. 4 Measured and EMTP / FDTD simulation results of a tower voltage in a chemical plant

V. CONCLUDING REMARKS

A transient analysis in transmission lines started in 1920s when lightning caused a transformer breakdown. Although a circuit-theory based approach involves problems related to the assumption and the application limit, still it is very powerful to analyze the power system transient. A numerical electromagnetic analysis is becoming another powerful approach especially to solve a three-dimensional transient and a non TEM mode transient. However, it requires large computation resources, numerical instability and reliability which are expected to be overcome near future by ICT technology advancement such as parallel computing.

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